Qualitative Models in Ecology

and their Use in Learning Environments

by

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“Creio numa força imanente que vai ligando a família humana
numa corrente luminosa de fraternidade universal.
Creio na solidariedade humana.
Creio na superação dos erros e angústias do presente.”

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Abstract

This thesis is concerned with the development of qualitative modelling approaches that can be used in educational contexts for simulation and explanation about ecological systems. Students have to learn about complex systems, and computers have great potential for providing tools to support ecology teaching. Most of the simulation models created so far for this purpose are based on mathematical equations. However, quantitative data is often missing. Moreover, mathematical models hardly can support explanations because they lack explicit representation of concepts about the system being modelled and of the causal relations between the modelling components. Qualitative Reasoning has the potential for handling these problems, as it provides ontologies and techniques for building models with qualitative and incomplete knowledge. Accordingly, different modelling formalisms are explored and compared in this thesis.

The specific domain chosen is the ecology of the vegetation of the Brazilian cerrado. Recurrent issues in scientific research and teaching are the effects of fire on flowering, germination, establishment, mortality of the cerrado plants, and on the succession of cerrado communities. The qualitative knowledge involved in these issues is represented in a domain theory of plant population dynamics. To implement this domain theory, a framework is proposed in which the structure of the system being modelled is represented as a combination of the conceptual, the causal and the mathematical components. The conceptual structure includes knowledge about the objects, their quantities, quantity relations, typical scenarios, and the mechanisms causing changes in the system. The causal structure is a representation of how changes start and propagate within the system. The mathematical structure is a description of the constraints between the quantities and the procedures for calculating their values. General guidelines for building qualitative models to be used in education are also discussed.

A number of models about different ecological problems are developed using the ontology provided by the Qualitative Process Theory (QPT) of Forbus, the qualitative algebra developed for Guerrin's System of Interpretation of Measurements, Analysis and Observations (SIMAO), and the data structures adopted in the qualitative reasoning shell GARP developed by Bredeweg. Some models are implemented in GARP. In models about the life cycle of cerrado plants, qualitative equations are used to assess the magnitude of the quantities, which in turn are used to determine state transitions. In models about the dynamics of populations and communities, state transitions are determined by the assessment of the causal influences between the quantities.

These models can be used for the automatic generation of different kinds of explanations in learning environments. It is shown that if only the mathematical and the causal structures are explicitly represented, the models support explanations about how the values are being calculated. However, if the conceptual structure is also explicit, it is possible to explain why the calculations are being done on the basis of domain knowledge. A set of topics for the explanatory discourse about concepts

expressed in qualitative simulations is presented, and the potential of qualitative models for supporting explanations in learning environments is discussed.

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Chapter 1 Introduction

This thesis is concerned with the development of modelling approaches that can use qualitative ecological knowledge for simulations and explanations in computer-based educational tools.

Probably, the first question to be answered refers to the type of knowledge involved in this task. What is qualitative knowledge? Before answering this question, consider the following statements:

(s.1.1) 'Águas Emendadas is located at the heart of the cerrado vegetation.'
(s.1.2) 'Cerrado is a tropical type of vegetation.'
(s.1.3) 'Cerrado covers some 2 million square kilometres.'
(s.1.4) 'The area covered by the cerrado is smaller than the Amazon forest.'
(s.1.5) 'The cerrado covers a large area, but this area is decreasing.'

Statements (s.1.1) and (s.1.2) can be identified as qualitative knowledge without problem. There are no doubts also that (s.1.3) is quantitative knowledge. What about statements (s.1.4) and (s.1.5)? They are qualitative representations of quantitative knowledge. This is how we express numerical properties of the world in qualitative terms.

From this, it is possible to recognise two types of knowledge[1]: quantitative and qualitative knowledge. The former is knowledge that can be expressed with numbers, and manipulated by mathematical equations. Qualitative knowledge, in turn, is non-numerical knowledge. It may refer to properties of the world that cannot be described with numbers at all (as the statements s.1.1 and s.1.2), but may also refer to knowledge about quantities (as in the statements s.1.4 and s.1.5).

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[1]Functional definitions in terms of procedural and declarative of knowledge (see for example, Anderson, 1988) are not relevant for the work described in this thesis.

This thesis is concerned with qualitative representations of quantitative knowledge. There are at least three classes of qualitative knowledge. These are exemplified by the expressions 'smaller than', 'large' and 'decreasing' in statements (s.1.4) and (s.1.5). The different roles these types of knowledge play in reasoning qualitatively about ecological systems will be shown.

In addition, this thesis is related to the use of qualitative knowledge about quantities in an educational context. Much of what students learn about ecology can be expressed in qualitative terms. So the use of computer-based methods in ecological education should be based on a sound understanding of how to represent and reason with this type of knowledge.

The research described here is therefore at the intersection between Ecology, Artificial Intelligence and Education. Trends from these three themes are discussed below.

1.1 The first theme: Ecology

When building models, the following maxim is to be kept in mind:

(s.1.6) 'The world is the world. Then there is how we think the world is, how we represent the world, and how other people read our representation of the world.'

It goes almost without saying that ecology deals with complex problems, most of which are not yet understood. In tropical areas the problem is even worse, not only because there are few studies about the ecology of these areas, but also because of the huge biological diversity. This is the meaning of 'world' in the statement (s.1.6).

Ecology is a relatively new science, and ecological theories are under development. So, we are still trying to understand 'how the world is'. As a consequence, ecological knowledge is often non-formalised (we are far from those elegant mathematical equations for representing quantitative ecological knowledge!), descriptive and expressed verbally or diagrammatically in qualitative terms.

'How to represent the world' is a problem for ecological modellers. Mathematical equations have been the main representational scheme used so far. However, the quantitative knowledge required for this approach is scarce and incomplete, and there are no tools for organising and processing the qualitative representations of numbers and mathematical equations.

Simulation models about ecological systems used in education thus far are also based on mathematical equations. 'How other people read our representation of the world' may be a problem, especially if these people are students of ecology trying to understand sophisticated numerical operations. We want models that can be inspected by the students, and explained in a language they are able to understand.

All in all, there is a need for different representations of quantitative ecological knowledge to be used in education. Here this work meets the second mainstream.

1.2 The second theme: Qualitative Reasoning

Explaining qualitatively the behaviour of physical systems (modelled with mathematical equations) was the motivation for the development of the Qualitative Physics in the 70's. Nowadays Qualitative Physics is known as Qualitative Reasoning (hereafter QR). This is an area of Artificial Intelligence concerned with the description of continuous properties of the world using a discrete system of symbols. The discretization is guided by the representation of qualitatively different behaviours of the system.

It is intriguing to realise that qualitative representations of quantities are found to be useful in physics. This is a well-established science, with several well-known principles about the most fundamental things, such as energy and matter. Physics also has a well-developed and formalised (mathematical) language for representing and reasoning with quantitative knowledge. However, qualitative knowledge is crucial in physics. In any problem solving activity, it is necessary first to understand the problem, then select the correct set of equations, and finally interpret the results. All these steps involve qualitative reasoning.

QR may have some solutions for the problems described above. However, how general are the theories and techniques developed in physics and engineering? Can they be applied to different domains? What unexpected problems will arise in different areas? New applications are among the most important research topics for the QR community.

Ecology is a challenging domain for QR, both for theoretical and practical reasons. Firstly, while physics is axiomatic and comprehensive, ecology is descriptive, heuristic and incomplete (Porter *et al.*, 1988). Secondly, given the complexity of ecological systems, it is very likely that new problems will arise. Finally, there are pragmatic interests involved. Interpretation and control of remote ecosystems, for example in spatial research, is an issue that soon will require some sort of approach (Guerrin, 1994).

Another research goal both for ecology and QR is the formalisation of the modelling process. As computers become widely used, the importance of modelling is increasing. Non-modellers would benefit from having tools for helping them to express their ideas.

QR is concerned with explicit representations of intuitions and common-sense knowledge used in problem solving. If this knowledge is explicitly represented, it may be useful for supporting explanations and other educational interactions. This brings us to the third theme.

1.3 The third theme: Education

The pedagogical value of learning by doing is already established. Learning environments based on simulation models are particularly interesting in domains like ecology, because simulations with real world ecological systems are rarely possible.

However, students often need some handles for understanding the concepts involved in a problem-solving activity. Ideally, explanation should be derived directly from the models, and produced dynamically during the simulations. This would ensure that the explanation is always updated and contextualized, at least with respect to what is going on with the system during the simulation.

If the simulation is based on mathematical models, explanation is limited by two factors. Firstly, only the quantities and the mathematical operations are represented. There are no explicit references to other elements in the world or conditions for the phenomena to happen. Secondly, explanations often draw on causal relations, and causality is hidden in mathematical models.

The work described in this thesis is faced with the challenge of creating models based on qualitative ecological knowledge which can be used in learning environments for both simulations and explanations. This challenge gives rise to the following research issues.

1.4 The objectives

The general objective for the work presented in this thesis is

> *to develop modelling approaches for representing qualitative ecological knowledge in models that can be used for educational purposes.*

In order to achieve this goal, it will be necessary

> *to explore the potential of QR modelling formalisms for representing ecological knowledge.*

and

> *to investigate the potential of qualitative models as the basis for explanations in learning environments.*

This study includes the following objectives:

to compare and evaluate these approaches with respect to the
vocabulary they use for representing the domain,
possibility of generating causal explanations ,
characteristics of the simulations.

Having in mind the importance of developing mechanisms for supporting the modelling process, another objective is

to investigate the process of building qualitative models in ecology.

1.5 Organisation of the thesis

This thesis is organised as follows:

Chapter 2 is concerned with an overview of the main problems involved in modelling vegetation dynamics for educational purposes. Qualitative knowledge is identified in ecological research. The main QR formalisms are discussed and their suitability for modelling the class of problems this work is concerned with is evaluated. Finally, the generation of explanations, in particular from qualitative models, is reviewed.

Chapter 3 presents the domain knowledge: the ecology of fire in the Brazilian cerrado. The cerrado is a large ecosystem with different types of communities, heavily influenced by fire. Knowledge acquired from Brazilian researchers provide the contents for the modelling effort described in this thesis.

Chapter 4 sets the fundamentals for a qualitative theory about vegetation dynamics. A framework is proposed for building qualitative models focusing on concepts, causal relations and mathematical operations. Domain knowledge requirements are matched with the modelling formalisms chosen for building the models. The chapter ends with a discussion about how to build qualitative models for educational purposes.

Chapter 5 describes simulation models based on qualitative equations that explore the magnitude of the quantities. Simulations in this case run over one time step. The focus is, therefore, on what is happening with the system during a particular state. Qualitative modelling languages and models are compared with mathematical models about the same problem.

Chapter 6 describes simulation models based on causal relations between the quantities. Simulations run over multiple time steps and involve increasing levels of complexity.

Chapter 7 is concerned with how explanations can be generated from qualitative models. The modelling primitives are used to provide the basic concepts for building the explanatory discourse. Knowledge is organised in topics, and the potential for explanations is demonstrated.

Finally, Chapter 8 presents a discussion and concluding remarks.

Chapter 2 Modelling ecological knowledge for simulations and explanations

Computer based simulations are becoming more important for ecological modelling. A number of new textbooks have been published recently (for example, Haefner, 1996; Gillman & Hails, 1997), a sign of the fresh air in the area. As these textbooks show, ecological modelling has been thus far almost synonymous with building mathematical models. However, this approach may not be suitable for representing much of the ecological knowledge. Ecological knowledge has been characterised as fuzzy, uncertain, incomplete, sparse, empirical, and non-formalised. It is often expressed in qualitative terms, verbally or diagrammatically.

Rikyel (1989) noted that, even expressed this way, this knowledge may be useful for many purposes. Many questions of interest in ecology (especially for teachers and decision makers) can be answered in qualitative terms (for example, using notions such as small/big, increasing/decreasing). Also scientifically valid qualitative predictions can be made when quantitative predictions cannot. Rikyel concludes that there is a need for new and efficient computer-based tools for making this knowledge explicit, well organised, processable, and (the main challenge) integrated with quantitative knowledge.

Some interesting lines of research related with representing and reasoning with qualitative knowledge are reviewed in this chapter. Section 2.1 presents a brief overview of different approaches for mathematical modelling in ecology. In section 2.2, the focus is on qualitative modelling without Qualitative Reasoning (QR). These works show some of the main problems that have been tackled by the QR community. In section 2.3 some of the main representative research in QR is explored and evaluated according to the needs of building models for simulations and explanations in learning environments. Finally, in section 2.4, literature related to using qualitative models for explanation generation is reviewed.

2.1 Mathematical modelling of ecological systems

This section is concerned with an overview of the most common paradigms used in ecology for modelling with mathematical equations. There is no intention of a deep discussion about any of these models, because this thesis aims at the development of qualitative modelling approaches.

Simulation models based on mathematical equations may be classified according to some modelling paradigms (see, for example, Robertson *et al.*, 1991). The most important are:

a) *Differential equations*. According to this modelling approach, the system is represented by a set of ordinary differential equations. Implicit is the notion that the system is changing continuously, and that rates of change are instantaneous functions of the current state of the system. This approach is often used for expressing the dynamics of physical systems. There are established numerical methods for solving these equations.

b) *System Dynamics*. This is a version of differential equations models. The system is represented as a set of compartments (the state variables), with flows of 'substances' between them (hence the other name for this paradigm, compartment-flow modelling). A differential equation describes the dynamics of each compartment. It is the resultant from the sum of all the inflows into the compartment minus the sum of all the outflows. Each flow is represented by an equation that links the rate of the flow with the values of the state variables, parameters and other variables. This is probably the most used modelling paradigm in ecology. It is very close to the way ecologists think about ecological systems. There are some toolkits available for building System Dynamics models, such as FloMo (see Chapter 5). These toolkits have a graphical interface, and can be used by non-modellers to create complex and realistic models without entering a single equation.

c) *Difference equations*. In this model paradigm, time is represented in discrete units (e.g. one year). This way, changes in the system are also represented as if they occur discretely. This approach corresponds to many ecological phenomena (for example, reproduction in some species happens just once a year, during very short time intervals). It can also be used for representing steps in continuous processes (for example, representing plant growth on a discrete basis, such as annually).

d) *Matrix population models*. This approach can be used for representing the dynamics of the population in terms of age-classes. It may be useful for calculating the value of key parameters of the population by means of the analysis of the matrix.

e) *Markov chain models*. This approach is based on a finite number of states, and on the probabilities of transitions between states. It can be used to model events such as succession.

f) *Cellular automata*. This approach provides a simple paradigm for representing spatially-organised systems. For example, the Game of Life is a game in which each cell on a grid may or not contain an individual. The fate of the individuals (death, survival, or reproduction) is defined in terms of the presence of other individuals in neighbour cells.

g) *Object-oriented modelling paradigm*. In this paradigm, objects are organised according to classes hierarchically organised. It may be useful for representing the creation and the disappearance of individuals, message passing between individuals, and inheritance of attributes.

The differential equations and System Dynamics modelling frameworks are of particular interest for the study described in this thesis. As it will be discussed below (section 2.3), the main QR formalisms are closely related to these two numerical modelling approaches.

2.2 Modelling with qualitative ecological knowledge

The main problems for modelling the continuous properties of ecological systems with qualitative knowledge are discussed here in the context of three research lines: using qualitative values for calculating the values for quantities of interest (Pivello, 1992), deriving behaviour from the structure of ecological systems (May, 1973), and generating causal explanations from qualitative knowledge about ecological processes (Walker & Sinclair, 1995). The section ends with the discussion of two modelling approaches representing the dynamics of communities in the cerrado: using vital attributes (Noble & Slatyer, 1980) and focusing on transitions between states (Pivello & Coutinho, 1995).

2.2.1 Modelling qualitative magnitudes of quantities

Reasoning about the effects of fire on the vegetation involves a number of continuous quantities. For example, in order to evaluate the amount of heat released in a fire event, it is necessary to calculate the amount of fuel available. However, as typically occurs in tropical areas, data about the cerrado have many limitations: there are few long term studies; quantitative information is scarce; and the characteristics of the majority of species are unknown. As a consequence, scientists, management workers, teachers and students have to draw conclusions from qualitative knowledge supported by common-sense theories.

Pivello (1992) reports the use of qualitative information about the environment for assessing the risk of fire in different communities of cerrado. An expert system (FIRETOOL) developed to support decision-making in the management of conservation areas in the cerrado is described. Given input information provided by the user about the site and the local conditions, FIRETOOL makes an interpretation of the current situation and recommends what might be the best management practice.

One of the modules of FIRETOOL is concerned with estimates of the risk of accidental fires. This normally requires quantitative data about fuel biomass, humidity of the fuel and of the vegetation, relative humidity of the air, wind, and the amount of heat released in a fire event. However, there are few data or mathematical models available on these issues. Pivello summarises her observations in tables where the values of the quantities are expressed in qualitative terms. The risk of fire is assessed by consulting several tables and combining values of intermediate quantities. For example, these operations may be something like

> 'IF moisture of the whole vegetation is low, and the proportion of dead material is high, and the moisture in the dead material is low, THEN the potential of fire is high.'

For the purposes of the present work, this approach for handling qualitative knowledge has at least two limitations. First, the mathematical operations used for calculating the values of the quantities are implicit in the tables. Thus it is not possible to create general simulation predictive models from her data. Suppose Pivello's data were real numbers instead of qualitative values. They could probably be condensed in a set of mathematical equations, useful for precise predictions about fire risk or intensity. It is desirable to have similar general qualitative models for supporting predictions about the effects of fire on the dynamics of the vegetation. Also implicit in the tables are the causal relations between the quantities. Therefore it is not possible to generate causal explanations from the tables containing knowledge collected by Pivello. In summary, this work points out the need for mathematical methods for operating qualitative values, and the importance of having explicit representations of causal relations between the quantities.

2.2.2 Modelling dynamic ecological systems with qualitative values

The need to incorporate qualitative knowledge in ecological modelling has long been a concern among ecologists. For example, May (1973) describes a model created within the framework of qualitative stability analysis, a theory developed in the context of economics.

The word *qualitative* has been used by economists for describing mathematical models based on signs that express the direction of change of the quantities. The motivation for the development of these modelling approaches is the need to handle complex systems when there are no quantitative models and data available. There is a historical connection between these efforts and the QR research, explained in MQ&D[2] (1995).

May (1973) noted that ecology is in a similar situation to economics, with respect to the lack of quantitative data, and explored the qualitative stability approach for studying the dynamic aspects of communities. He was interested in the relationship between complexity (defined in terms of the number and nature of the individual links in the trophic web) and stability (defined by the tendency of returning to the equilibrium after small perturbations). Most of the modelling approaches to these problems make assumptions about the magnitudes of the interactions between species in the community. May's research question was to investigate what can be said if only the topological structure of the trophic web is known, i.e., knowing only the signs (–,0,+) of the interaction between the species.

Each of the components of the food web is a population that may be increasing, stable, or decreasing depending on the interactions with other populations. May described the interactions between the species in a matrix in which each element represents the effects of a population on another population. In this system, the effect of population A on B is either { –, 0, + } depending respectively on whether the population B decreases is unaffected or increases in the presence of population A. For example, predation is an interaction between two species in which one (predator) increases in the presence of the other species (the prey), while the population of prey decreases in the presence of the predator. This situation can be described as (+,–). In a similar way, four other categories are defined: competition (–,–), amensalism (–,0), comensalism

[2]MQ&D stands for 'Modélisation Qualitative et Décision', the name of the group of French researchers in QR.

(0,+), and symbiosis (+,+). Data of this kind can easily be obtained by inspecting a diagrammatic representation of the food web, even in the total absence of any quantitative information.

Based on the model, May was able to derive some conclusions about the stability of small communities. For example, he showed that the 'common-sense wisdom' that more complexity means increased stability may not be true. In his simulations, a less complex community met the conditions for stability, while the more complex was not stable. It is pointed out that the biological characteristics associated with the criteria established by the qualitative stability theory make the approach useful for modelling quite complex food webs. However larger populations violate some of the criteria. In these cases, the signs of the interactions alone are not enough for stability analysis, and the interaction magnitudes should be taken into account. All in all, May concludes that this can be a useful approach for capturing the general tendencies of the system, bypassing long and complicated steps required by numerical models.

Apart from the historical aspects, this paper is interesting because it shows that ecological processes can be represented as differential equations, but the interpretation of the results may be done in qualitative terms. While Pivello's work (section 2.1.1) involves reasoning with the magnitudes of the quantities, May deals with change over time, that is, with the derivatives of the quantities. This approach is common in the QR research line developed by de Kleer & Brown (1984), discussed in section 2.2. Again, causal explanations cannot easily be derived from this model, because causal relations are not explicitly represented in mathematical models.

2.2.3 Modelling causal relations for explanations

Generating causal explanations based on qualitative ecological knowledge is one of the main concerns of the work described in Walker & Sinclair (1995). These authors describe a knowledge-based approach to decision support for agroforestry research and extension programmes.

They report the development of toolkits for creating knowledge bases and reasoning with indigenous ecological knowledge. Knowledge bases can be created by using a domain-specific grammar, developed for capturing qualitative knowledge that may or may not represent quantities. This knowledge includes descriptions of the components of agro-ecosystems and the effects of ecological processes.

The grammar is based on unitary statements that can be used to express causal relations between objects, inequality relations between quantities (such as 'greater_than', 'less_than'), and descriptions of the behaviour of the system's components (for example, 'increasing', 'decreasing, 'no_change'). A range of inferential mechanisms were developed for causal reasoning using the formal statements developed with the grammar, and supports the generation of causal explanations.

Walker & Sinclair point out that the development of knowledge bases by different individuals, or the representation of knowledge obtained from different groups of informants, may be facilitated by the use of templates. For example, they identified some fundamental ecological processes (such as shading, rainfall interception, nutrient cycling) that were described in different knowledge bases developed during the project. By using common templates, they argue, it may be easier to create knowledge bases that are generic in their contents and that can be successfully combined.

This work is interesting for the research described in this thesis because it shows:
a) the relevance of ecological processes in the common-sense knowledge of farmers and traditional populations;
b) the importance of ecological processes for grounding causal explanations;
c) the need for general models about ecological processes. According to Walker & Sinclair, natural language-like statements are inadequate for general representations of causal relations. A common representation for processes would provide a more generic knowledge bases and the possibility of combining different knowledge bases.

The three approaches reviewed so far suggest the need for modelling approaches that incorporate qualitative knowledge about the magnitude and the derivative of the quantities. There is also a need for structured representations of ecological processes that can be associated with causal explanations.

2.2.4 Modelling vegetation dynamics

In this section, two approaches for building qualitative models about the succession of communities are discussed. The first approach (section 2.2.4.1) uses life cycle traits to classify the species and explain their behaviour after disturbance. The second (section 2.2.4.2) explains succession in terms of states and transitions. Both were used for modelling cerrado communities, and may be helpful for the understanding of the problems involved in qualitative representations of populations and communities.

2.2.4.1 Qualitative models based on vital attributes

Noble & Slatyer (1980) proposed an approach for building qualitative models about the dynamics of communities subject to recurrent disturbance (such as fire). This approach is based on a small number of attributes of the plant's life history (vital attributes) which can be used to characterise the potentially dominant species in a particular community, under different types and frequencies of disturbance.

Species are classified according to their mechanisms of arrival and persistence in a site after the disturbance, their ability to establish and grow to maturity, and the time taken to reach critical stages in their life cycle. This is a very detailed system for grouping species with similar behaviour, with 20 possible combinations, from which 10 are biologically feasible and 8 are common in nature.

Simulations with models of this type typically produce a replacement sequence which depicts the major shifts in composition and dominance of species which occur following a disturbance. At each state, the community is defined by the presence of a sufficient number of individuals in particular stage of their life cycle (for example propagules, juvenile or mature).

This approach can be useful in the management of natural and disturbed ecosystems, particularly in situations in which presence or absence of a species is the basic information required. As noted by Noble & Slatyer (1980), the vital attributes scheme (in this original formulation) is unable to describe which of the several species, at a comparable life stage, may be dominant in terms of relative biomass or relative density.

The limitation in the representation of continuous properties of the communities (such as biomass and density) was overcome by Moore & Noble (1990; 1993). They describe a simulation model based on the vital attributes, but combined with knowledge about the abundance of the populations and their survival according to the availability of environmental resources. These quantitative aspects are handled by mathematical models. Population sizes and certain vital attributes (e.g. germination rate) are stored internally in the model as real numbers. However their values are mapped into discrete scales and presented in qualitative terms such as {low, medium, high} in the final output. This makes the qualitative simulation model useful for predictions that could be used in decision making (Moore & Noble, 1990).

2.2.4.2 Succession models based on state-transition

A different approach to qualitatively modelling the succession in cerrado was explored in Pivello (1992) and further developed by Pivello & Coutinho (1995). It is based on a 'state-transition' paradigm, which views succession as a multiple pathway process. Each distinct succession stage is called a 'state', and the actions that direct them to other states are called 'transitions'. Two types of states are identified: stationary and transient. The former corresponds to more stable and persistent communities, while transient states last for short time periods. Transitions may include disturbance of different types and intensities, and even stochastic events. Pivello & Coutinho (1995) identified 11 types of communities and 42 possible transitions, corresponding to fire, grazing and wood cutting under different environmental conditions. The resulting model is qualitative in its formulation, and simple enough to be understood and used by managers of cerrado conservation areas. However, as the authors acknowledge, experimental research is required to validate the model.

Describing changes in the structure of the communities requires reasoning with quantitative knowledge. Detailed representations of the characteristics of the species are important, but quantitative knowledge is very relevant to the understanding of succession. These are the lessons learned from the modelling effort described in the previous section.

The state-transition model presented by Pivello & Coutinho (1995) does not deal explicitly with qualitative knowledge about quantities. However it is relevant for the work described in this thesis because it sheds some light on the effects of disturbances at different stages of the succession in communities of cerrado, and offers a possible modelling solution. These points will be further explored in Chapter 6.

2.3 Qualitative Reasoning approaches

> " I started thinking about what knowledge was required to solve classical physical problems and how to build a system that could solve them. (...) The research showed that qualitative reasoning is critical for comprehending the problem in the first place, formulating a plan for solving the problem, identifying which quantitative laws apply to the problem, and interpreting the results of quantitative analysis."
>
> (Johan de Kleer, in Weld & de Kleer, 1990, p. 2)

Qualitative Reasoning (QR) is an area of Artificial Intelligence (AI) which creates representations for continuous aspects of the world (such as space, time and quantities) to support reasoning with little information.

As pointed out by de Kleer & Brown (1984), outstanding problems in physics, education, psychology and artificial intelligence motivate the development of this line of research, to predict and explain the behaviour of physical systems in qualitative terms. The main goals of this research line are:

a) to develop modelling approaches that are far simpler than classical physics and yet retain all the important distinctions without invoking the mathematics of continuously-varying quantities and differential equations;
b) to produce causal accounts of physical mechanisms that are easy to understand;
c) to provide common-sense models for the next generation of expert systems.

These objectives have not been completely achieved yet, but a wide range of different formalisms, techniques and applications have been developed. QR has been of great interest in different areas, and good reviews of the field are available. For example, Weld & de Kleer (1990) provides a collection of classic papers, including Forbus's 'Qualitative Physics: Past Present and Future', an account of the main ideas and research problems. The *Artificial Intelligence* journal has published two collections of papers on this field: in 1991 (volume 51, numbers 1-13), and in 1993 (volume 59, numbers 1 and 2), the latter with the personal view of some of the most prominent researchers in the area. Another important reference is the book by Kuipers (1994), which focuses mainly on his program QSIM (see section 2.2.1.3). The proceedings of the annually-held International Workshops on Qualitative Reasoning include the latest developments in the area (see, for example, Bredeweg, 1995; Iwasaki & Farquhar, 1996; Ironi, 1997). An extensive review of the literature and the main tendencies was published by the QR French group (MQ&D, 1995). Of particular interest for this thesis is the review of QR in ecology by Guerrin (1997) and the special issue of the journal *Interactive Learning Environment* (volume 5), with a general introduction to the area by Bredeweg & Winkels (1997).

2.3.1 Comparing QR approaches

This section presents a comparative study of the three most important QR formalisms: the component-based approach (de Kleer & Brown, 1984), the constraint-based approach (Kuipers, 1984; 1986; 1994) and the process-based approach (Forbus, 1984). Initially a simple ecological system consisting of few variables is used to guide the comparison. Since System Dynamics (SD) is a modelling approach widely used in ecology, which has many similarities to the three QR formalisms, a description of a model of this problem in SD is included for comparison. Bearing in mind the educational application for the models, these approaches are compared with respect to the

a) vocabulary used to describe the system and its potential for explanations;
b) possibility of deriving causal explanations from the model;
c) characteristics of the simulation with models developed according to each of these approaches.

A version of this comparison is presented in Salles *et al.* 1996b.

2.3.1.1. A simple ecological problem and a numerical model for it

Suppose we want to model the behaviour of a plant population under different conditions, to communicate the knowledge involved to undergraduate students. Plants germinate from seeds, grow up, produce flowers which might produce seeds, and die (although death can occur at any stage of their life). A plant population can be increasing, decreasing or stable over a certain period of time.

In order to represent this simple ecological system and simulate its behaviour, a model should include the plant population, the available stock of seeds, and appropriate flows. The inflow, recruitment, represents the portion of seeds that germinate and produce new plants that are incorporated in the population. The outflow, mortality, represents the death of plants that have actually been introduced to the population by means of the recruitment.

A System Dynamics (Forrester, 1961) model of the problem might consist of one state variable (number of plants), an outflow (mortality), and an inflow (recruitment) influenced by an intermediate variable (number of seeds) which in turn is influenced by the population size. The structure of the system could be represented by a differential equation that describes the variation in the state variable over time according to the inflow and the outflow.

Formulating the right equation and calibrating it is a difficult task, but once done this model would support simulations and, therefore, predictions about the population size. The use of this model for explanation generation would however be limited by lack of explicit vocabulary about the system's elements, and lack of explicit causality.

2.3.1.2 Modelling according to the component based approach

Three kinds of constituents are considered in the component-based approach: *materials*, *components* and *conduits*. Simulation of system behaviour is accomplished by operating on and transporting materials. Only components can change the form and the characteristics of materials. Conduits transport material from one component to another, but do not change any aspect of the material being transported.

The goal is to draw inferences about the behaviour of a composite device solely from laws governing the behaviour of its parts. Thus one of the most important axioms in this approach (and of QR in general) is the *no-function-in-structure* principle, according to which the laws of the parts of the system must not presume the functioning of the whole. Behaviour is described in terms of the material's attributes. An attribute represents a set of variables, each of which can be referenced by a law. This approach was implemented first in a program called ENVISION (de Kleer & Brown, 1984).

The central modelling tool is the *confluence*, a qualitative differential equation. For example, consider the population of plants as a component. The qualitative behaviour of a plant population can be expressed by the confluence $\delta N = R\ [-]\ M$, where δN is the variation in the number of plants, R is recruitment, and M is mortality and [−] is an operator for representing qualitative subtraction. A confluence relates multiple tendencies: recruitment positively influences the population growth, while mortality influences it negatively. However, a single confluence can rarely characterise the behaviour of a component over its whole operating range. The range must be divided into different regions, each of which is described by a different set of confluences. The assignment of values to every variable in the confluences in a particular region defines a *qualitative state* (de Kleer & Brown, 1984). For example, qualitative states for plant populations can be 'increasing', 'stable', 'decreasing'.

Qualitative variables can only take one of a small number of values, determined by their *quantity space*. A qualitative algebra is required in order to combine these qualitative values. In the component-based approach, a simple quantity space to represent whether a quantity is increasing, decreasing or unchanging ({+, 0, −}), is enough for most applications. This is not the case in ecological modelling. Very often it is necessary to represent and combine a wide range of qualitative values for heterogeneous variables (Guerrin, 1991;1992).

The physical structure of the system is represented by a topology in which nodes represent components and edges represent conduits. Once defined, the topology cannot be changed. It is difficult to represent things that appear and disappear during the reasoning process. For example, a new topology should be defined to include nectar and pollen in our model. Each component is represented by a component model that consists of the confluences that describe the component's behaviour and the set of possible qualitative states, including *specifications* (statements about the conditions for the state to be active). Table 2.1 represents the component model for the plant population:

component	**qualitative states**	**specifications**	**confluences**
plant population	increasing	$R > M$	$\delta N = +$
	stabilised	$R = M$	$\delta N = 0$
	decreasing	$R < M$	$\delta N = -$

Table 2.1 The component model for plant population.

As the system evolves, qualitative values of the variables change, causing transitions between states. State transitions are governed by some rules, and each qualitative behaviour of the device being modelled is a path through the state transition diagram. Diagrams containing all the possible states resulting from solving the confluences, and a causal account for the behaviour constitute the *total envisionment*.

Envisionment is done in two stages. First, all the possible states for each individual component are determined and combined with all the possible states of the other components in the model. This is called the *intrastate analysis*. For example, intrastate analysis should reveal how the value $\delta N = +$ (state 'increasing' of the population) would propagate in the system and change values in confluences of the other components, such as the seed bank, recruitment and mortality. The second stage is the *interstate analysis*, when all the legitimate transitions between states are determined. In our example, if the population's state is 'increasing', then the following state can be either 'increasing' or 'stable' but not 'decreasing', because qualitative values cannot be skipped (the so-called *continuity rule*).

The component-based approach and related research in causal reasoning (see section 2.4) were developed in electronics, a domain where real systems (devices) are closer to idealisations (models) than ecology. Devices have well-defined topologies, built to achieve specific behaviours (teleological systems). The behaviour of their components can be understood by the application of well-established physical laws. This pioneer work evolved into an important area of research called *model-based diagnosis*. Ecological systems hardly share these characteristics. However, there is a role for the model-based approach in modelling controlled micro-ecosystems, such as the crop-irrigation system described in Plant & Loomis (1991).

2.3.1.3 Modelling according to the constraint-based approach

In the constraint-based approach, there is neither explicit representation of entities from the real world, nor libraries of model fragments. The starting point is the *qualitative differential equation* (QDE), which is an abstraction of the ordinary differential equation. The constraint-based approach is not a complete ontology as are the other two studied in this section, it is a qualitative mathematics, formalised to support the prediction of behaviour from qualitative constraint equations. This approach was implemented in a program called QSIM (Kuipers, 1986). Constraint-based models can be generated either by re-writing ordinary differential equations, or by creating QDE's from descriptions of the system's causal structure (for an example, see Kuipers & Kassirer, 1983).

Quantity spaces contain values that represent the boundaries for describing qualitative distinct behaviours, called *landmark values*. The qualitative state of a variable can be a landmark value or the interval between landmark values. During simulation, it is possible to create new landmark values, that might represent unexpected behaviours. The qualitative state of a variable is specified by a pair $< qval, qdir >$, respectively, the qualitative value of the variable (*qval*, a landmark value or an interval between two landmark values) and the direction of change (*qdir*, the sign of the first derivative with respect to time). Time is represented as a sequence of points, as in the component-centred approach. When something interesting happens to any variable, a new time point is created. A state description with values for all variables is given at every time point.

Qualitative simulation consists of simulating the system forward from some initial state. Rules are used to determine the possible state transitions. It follows a generate-and-test algorithm: first generate all the possible successors from the initial state and then filter the solutions according to some constraints. When multiple possibilities occur, new branches are derived to accommodate all legal transitions. The result is a graph (the *behaviour tree*) containing all the states that can follow the specified initial state. Any path in this graph represents a possible behaviour. However, some of these behaviours are redundant (repetition of the same states) or spurious (physically impossible), and filters have to be used to avoid them.

There are seven types of constraints: arithmetic (addition, minus and multiplication), derivative, monotonic (increase, decrease), and constant. Some are straightforward relationships, such as add(x, y, z) to represent $x + y = z$, and deriv(x,y) to represent $dx/dt = y$. The functional constraints monotonic increase (M^+) and monotonic decrease (M^-) express incomplete, qualitative knowledge about a functional relationship. To model the plant population problem, variation in plant number must be related to recruitment and mortality. The result is the following set of qualitative equations: deriv(N,n). It follows that $n = R - M$. This can be re-written as $R = n + M$ and then represented as add(n,M,R).

QSIM produces excessive branching in the simulation graph. This occurs because, if a quantity is not involved in any constraint during a certain state of the simulation, then QSIM tries all the possible solutions for the derivative of the quantity, and the quantity will increase, decrease or remain stable in the next state. This is called chattering (Kuipers, 1994). The consequence of chattering is that the simulation may easily become intractable. Attempts are being made to solve this problem (for example, Clancy *et al.*, 1997).

However, the constraint-based formalism alone is as inadequate for building tutoring systems as numerical models. There is no explicit representation of the causal relationships. The only causal relationship available is the output sequence of values obtained after constraint satisfaction. The constraint-based approach can be combined with other approaches to overcome these problems (see below).

There are examples of constraint-based qualitative simulation with ecological systems, such as a predator-prey system (Kuipers, 1994). Guerrin (1997) describes the use of QSIM for modelling the effects of environmental factors on the dynamics of the population of salmon.

2.3.1.4 Modelling according to the process-based approach

The process-based approach is known as Qualitative Process Theory (QPT). It has been implemented in the program QPE (Forbus, 1990b), for example. In this approach a structural description of the system is given by a set of *individual views* and *processes*. The former describes objects and situations, the latter are the only mechanisms that promote changes in behaviour. Characteristics of objects are represented by *quantities*, and the qualitative state of a quantity is a pair *<amount,derivative>* . Changes in their values mean changes in qualitative states, and therefore changes in behaviour. Each quantity is associated with a partially ordered set of qualitative values, its quantity space. Some elements in this set can be *limit points* (if they correspond to discontinuous changes in the system). The task of checking if variables have reached limit points is called *limit analysis*.

In the process-based approach the concept of *histories* is used to describe the behaviour of an object over time. Since objects are often involved in more than one process, they have a process history. Also there is a quantity history because each quantity has its own distinguished time points. A complete object history is made up by these two kinds of history.

In the example presented above, the plant population's behaviour emerges from a combination of the following processes: *Seed_production*, *Recruitment*, *Mortality* and *Population_growth*. A process is described by five parts: *individuals*, *preconditions*, *quantity conditions*, *relations* and *influences*. An individual view is in turn described by the same first four parts of the process description.

The slot *Individuals* contains lists of objects or entities upon which the process acts, such as plants and seeds. *Preconditions* contains statements referring to external conditions. For example, the *Population_growth* process may require some environmental factors (such as water, light, nutrients) which can be explicitly represented. *Quantity Conditions* are statements about inequalities involving quantities of the objects, which can be used to determine whether or not a process is active. For example, *Population_growth* requires number of plants greater than zero. *Relations* are statements about relationships between quantities. Descriptions of new entities created by the process are also presented here. For example, seeds created by the process *Seed production* are represented in the *Relations* slot. This point contrasts with the component-based approach, in which the device topology must be completely specified at the beginning of the simulation.

An important primitive for describing relationships between variables is *qualitative proportionality*. Qualitative proportionalities (α_Q) express unknown monotonic functions between two variables. If, for instance, the function is strictly increasing, then a positive qualitative proportionality (α_{Q+}) is used. In *Population_growth* process for example, growth_rate is related to the number of recruited and dead individuals as follows:

$$[\text{growth\_rate}] \ \alpha_{Q+} \ [\text{recruitment}]$$

$$[\text{growth\_rate}] \ \alpha_{Q-} \ [\text{mortality}]$$

Qualitative proportionalities are similar to the functions M+ and M– used in the constraint-based approach. However, the latter express a 'closed world assumption', whereas the former does not exclude the possibility of the quantity involved in the proportionality be influenced by other proportionalities at the same time - they express an 'open world assumption'. Consequently, proportionalities can be used to build equations. We could re-write the proportionalities above as

$$[\text{growth\_rate}] = [\text{recruitment}] - [\text{mortality}]$$

In the process-based formalism dynamic aspects are expressed by the notion of *direct influence*. Direct influences can only appear in processes and are presented in the slot *Influences*. For example, the number of plants is directly influenced by growth_rate, and this influence is positive:

$$I+([\text{number\_of}(\textit{Plant})], [\text{growth\_rate}])$$

A single direct or indirect influence statement does not completely determine how the quantity it affects will change. Its effect must be combined with all the other influences acting on that quantity to ascertain their net effect. The operation of combining influences is called *influence resolution*. State transitions depend on influence resolution and limit analysis. Simulation in this ontology may produce *total* or *attainable* envisionment[3].

Compared with the two other approaches, the process-based formalism provides a broader set of modelling constructs for representing biological and ecological systems. Some examples are presented by Arana & Hunter (1992) in the domain of human physiology, and Hunt & Cooke (1994) in modelling the process of photosynthesis.

2.3.2 A combined approach to QR

The previous section suggests that alone none of the three main approaches can represent the wide diversity of physical (and ecological) problems. A unified theory for qualitative reasoning is desirable, and could expand the range of applications for qualitative models. This is the motivation for various works, such as Crawford *et al.* (1990) and Bredeweg (1992). Crawford *et al.* describe QPC, a program that is a combination of the process and the constraint-based approaches. QPC is a model builder that uses the constructs of QPT (views, processes, influences) to produce qualitative differential equations in order to run simulations in QSIM. For example, Heller *et al.* (1995) describe qualitative models involving spatial distribution of parameters and processes in hydro-ecological systems implemented in QPC, and Heller & Struss (1996) propose a formalism for building models about the dynamics of these systems. Rickel & Porter (1995) also used QPC to run simulations as part of the process of answering questions about ecological and botanical problems (see section 2.3).

This section discusses the work by Bredeweg (1992), which proposes a combined approach to QR. The goal of this research is to create a theory of qualitative prediction of behaviour that encompasses the three main approaches, with a better definition of

[3]Total envisionment refers to all the possible states of system, independent of any initial scenario. Attainable envisionment is, in turn, all the possible states following a specified initial scenario.

the various types of knowledge involved in behaviour prediction. This unified approach proved its viability in an implemented computer program (GARP) that realises the problem-solving ability specified in the model of expertise.

Bredeweg noticed that none of the three main approaches completely captures all the distinctions that are relevant for qualitative prediction of behaviour. Although they show a certain amount of similarity, each seems to be suitable for particular problem solving tasks (reasoning about devices that are networks of components, reasoning about the interaction between objects through processes). However, the precise relation between the conceptualisations used in each of the approaches is unclear.

The most important requirements for this unified theory are:
a) A broadly applicable ontology with a clear distinction between knowledge type and knowledge use. Bredeweg noted that in the definition of views and processes, there is an undesirable mixture of knowledge, referring to *what* is being modelled (the type of knowledge) and *how* that knowledge is used by the problem solver (the use of knowledge). For example, in the definition of the process *Seed production*, seeds created by the process appear in the slot Relations, although they are 'individuals' (see Chapter 2, section 2.3. . A clear distinction between different types of knowledge will improve the capacity for problem solving.

b) The representation of partial models used in both the component and the process-based approaches. A unified theory must accommodate model fragments like the component models (representing the behaviour of a single physical object), views (describing static properties of the system) and processes (for describing the behaviour of interacting physical objects).

c) A set of relations for representing both non-causal and causal relations between quantities. The unified approach must offer an extended range of modelling constructs that can be applied in different situations to express relations such as those modelled as confluences, and those modelled as proportionalities and direct influences.

d) A method for reasoning about inequalities at a higher level of detail, compared to the original implementations of the three approaches.

e) A focused search for states of behaviour, with the possibility of generating total and attainable envisionment. The unified approach should allow the generation of all the possible states from a scenario, with or without the definition of an initial state. It would be even better if the user could control the simulator and follow a particular path (sequence of states) in the envisionment.

f) The explication of reasoning steps during the simulation. The knowledge used during the simulation must be available for inspection by the modeller or by the user.

This unified approach is implemented in GARP (General Architecture for Reasoning about Physics). Bredeweg (1992) demonstrates that GARP supports building models both in the component and the process-based approaches. The former is illustrated in a model of a refrigerator, and the latter in models about balances. GARP was used for building models in different domains, such as heart diseases (Bredeweg, 1992), ecological principles applied to the organisational theory (Kamps & Péli, 1995), and population and community ecology (Salles & Bredeweg, 1997). GARP has also been used in a number of studies about tutoring interactions (see, for example, Koning & Bredeweg, 1996) and cognitive diagnosis (Koning *et al.* 1997a; 1997b).

2.3.3 Other approaches for modelling with qualitative knowledge

The QR approaches discussed so far do not focus specifically the problem posed by the type of data collected by Pivello (1992) and discussed in section 2.1.1. Interpretation of that kind of data requires reasoning about what is happening in a system while it is in a particular state, that is, during a period of time in which the system does not change. This problem was addressed by Guerrin (1991; 1992).

Guerrin describes SIMAO (System for Interpretation of Measurements, Analysis and Observations), a program developed for applications in the management of hydro-ecological systems. In this context, the variables are heterogeneous (linguistic observations, measurements and analysis expressed in numerical values). Guerrin proposes a system in which the values of the variables are translated into qualitative values, and propagated through a causal graph.

Expert knowledge about the quantities is encoded according to three types of rules: a) translation from numerical input values into qualitative values; b) translation of linguistically expressed values into qualitative values, and c) calculation of the values of unmeasured variables from the values of their causes. A qualitative algebra was developed for operations with a set of symbolic values expressing five intervals (e.g. {very low, low, medium, high, very high}). This algebra is based on operators that represent how the quantities combine. For example, when a quantity Q1 is combined with another quantity Q2 through the operator [x] (for qualitative multiplication), the possible results are described as {strong inhibition, inhibition, permissiveness, activation, strong activation}.

The qualitative algebra developed in SIMAO was applied to other biological problems. For example, SIMAO was applied to the interpretation of data relating to the fermentation process (Guerrin *et al.*, 1994). In their model of photosynthesis, Hunt & Cooke (1994) used a similar algebra and a six-valued quantity space (the same five values used by SIMAO plus the zero). Finally, SIMAO's algebra was later used to represent aspects of the life cycle of a plant population (Salles *et al.*, 1996a). This qualitative algebra was later extended to characterise quantities in terms of dualistic values (e.g. low/high; above/below, etc.) (Guerrin, 1995).

Other approaches to using qualitative ecological and biological knowledge in simulations have been described in the literature. Câmara *et al.* (1987) and Antunes *et al.* (1987) describe SLIN, a program that supports qualitative simulations using values expressed in linguistic terms (such as {low, medium, high}). SLIN was used in studies about the management of water resources (environmental impact assessment and pollutant dispersal). A different approach uses fuzzy numbers for representing qualitative variables (Schumoldt, 1991). In this case, every parameter is represented by a 'quantity' value and a 'change' value, both expressed as fuzzy numbers. This work, as well as Hunt & Cooke (1994) and Kamps & Péli (1995) are examples of reasoning with second order derivatives in problems about ecological systems.

2.3.4 "Modelling the modelling process"

The phrase above (Muetzelfeldt, 1991) poses a problem that is becoming more and more important for both the ecological modelling and the QR communities. Modelling is a process that requires massive idealisation, and that ends with a representation of complex phenomena in a much simpler and more tractable form. However, most of the modelling decisions are not explicit, and cannot be assessed and evaluated. Muetzelfeldt argues that it is important to develop mechanisms for objectively comparing alternative model designs, according to the purposes of a particular model.

A goal for the QR research is the formalization of the process of building models. This is essential for creating representations of different aspects of a system or for the system as a whole. As shown above, a recurrent notion in QR is that simulation models are born out of combinations of partial models (model fragments) stored in a library, according to specified circumstances. Mechanisms for the automatic selection of model fragments have been developed (see for example Addanki *et al.*, 1989), and today there is a well establish technique for this task - compositional modelling (Falkenhainer & Forbus, 1991).

In an extensive review of techniques for building qualitative models, Schut & Bredeweg (1996) observed that much effort has been spent so far in the selection of model fragments, but the development of the library itself has been largely ignored. The situation seems to be changing. For example, Clancy *et al.* (1997) describe a set of tools for supporting the user in the process of analysing simulation results and revising qualitative models developed in QSIM. Also Salles & Bredeweg (1997) discuss some general guidelines for the modelling process that can be applied in different domains. This point will be expanded further in Chapter 4.

It is interesting to note both communities engaged in the formalization of the modelling process as a requirement for helping non-experts in the task of building their own models. Muetzelfeldt (1991) points out that the biological understanding of non-modeller ecologists can be fully exploited if modelling is directly accessible for them. On the same line, the development of tools for supporting the process of model construction will facilitate the use of qualitative models in education by non-modellers.

2.4 Explanations and qualitative models

Qualitative Reasoning was born as a tentative of explaining the behaviour of physical systems in educational contexts. The pioneer was NEWTON (de Kleer, 1977), a program for solving problems in mechanics. In these 20 years, QR grew as a respectable area of research, and produced many theories and techniques that are being applied in many different areas. However, the original motivation remains, and many contributions for the development of educational tools are being reported.

In fact, the use of artificial intelligence in the development of educational tools has a long history. Relevant literature about this area of research includes O'Shea & Self (1983), Sleeman & Brown (1982), Wenger (1987), and Polson & Richardson (1988). Current research is presented in proceedings of conferences, the most important is the biennial AIED (World Conference on Artificial Intelligence in Education).

This section concentrates on the main contributions of QR for education, in particular for the generation of explanations in simulation-based environments.

2.4.1 Mental models

The most relevant contribution of QR for the development of learning environments was the final phase of the SOPHIE project (Brown *et al.*, 1982). The aim of SOPHIE was the development of reactive learning environments about electronics. In this environment, students were able to inspect electronic circuits and, by making measurements and testing hypotheses, decide what component was faulty. It became clear for the authors during the project that understanding the causal relations between the components of the system was the basis for understanding the whole system. However, the authors themselves admit that they "did not really know what it is meant to *understand* how a complex piece of equipment works." (Brown *et al.*, 1982, p. 279). The need for a theory about how humans understand complex systems led their investigations towards the concept of *mental models*.

Mental models (also referred to as mechanistic models or causal models) are the models that people use for thinking about physical systems, in particular to infer the functioning of devices from knowledge about their structure (de Kleer & Brown, 1983a). From this work on SOPHIE and mental models, de Kleer & Brown developed the basis for their theory of qualitative physics, which is at the root of QR. Their approach was discussed in section 2.3: the component-based approach (de Kleer & Brown, 1984).

Research about the formation and the use of mental models is a central topic for education in general and for the design of tutoring systems in particular (see discussion in Wenger, 1987). From the perspective of the research described here in this thesis, it is interesting to discuss how de Kleer & Brown's approach handles the generation of causal explanations.

Explanation is defined by de Kleer & Brown (1984) as the execution trace of whatever algorithm is used to make a prediction. Explanation and prediction are thus intrinsically linked: every syntactically valid explanation must describe a possible prediction. Thus, an explanation consists of a sequence of statements where each is justified by previous statements in the sequence. One structure that meets these criteria is the logical proof: the confluences in the component models and input signal(s) provide the givens, and justifications are presented in terms of simple logical inference steps.

The following is part of an explanation about why a stable population decreases if mortality (M) is 'operating' and the seed bank (S) is absent (see details about this problem in section 2.3). Given that recruitment (R) is calculated from the value of seed bank, and the premise S=0, then R=0. Given also the confluence $\delta N = R\ [-]\ M$ and the calculated value for R, then $\delta N = -M$. Substituting the given value $M = +$ in the confluence, it follows that $\delta N = -$.

It can be also shown that $\delta N = -$ by means of an indirect logical proof, the *reductio ad absurdum*, demonstrating that $\delta N = +$ would be contradictory (for detailed explanations about this procedure, see de Kleer & Brown, 1983b). Sometimes this indirect proof plays a crucial role in solving ambiguities.

However, the explanation-proof is inadequate as a theory of explanation, because of some undesirable characteristics. Steps in the explanation do not follow any notion of causal order, they move on from input to output in interstate behaviour. Thus explanation-proof explains *why* the device must behave, not *how* it behaves. As noted by de Kleer & Brown, explanation-proofs "embody the epistemological principle 'There is a reason for everything' at the expense of the ontological principle, 'Everything has a cause'. " (de Kleer & Brown, 1984, p.58).

To explain how a behaviour is achieved, it is necessary to explain what happens when the system is stable (intrastate behaviour). Moreover, a causal account for the changes in the system is required. However, confluences do not represent causal relations explicitly. To satisfy that ontological principle, de Kleer & Brown (1984) introduced the concept of *mythical causality*. This is a description of how a perturbation is introduced into the system by some (causal) action and causes disequilibrium. During this instant of perturbation, changes occur as a 'sequence' of non-equilibrium states affecting the quantities. These authors developed mechanisms for determining the mythical causality by the analysis of the propagation of disturbance within the system. This way de Kleer & Brown could produce causal explanations about the behaviour of the system without explicit representation of causal relations.

This concept was later challenged by Iwasaki & Simon (1986), to whom mythical causality was similar to already known methods for deriving causality from a set of equations, such as *causal ordering* and *comparative statics*. These are techniques used to identify causally dependent variables in a set of equations. In fact, as pointed out in MQ&D (1995), if there is no feedback loop in the system, mythical causality and causal ordering produce roughly the same account for corresponding sets of confluences and equations. However, if there is a feedback loop, then mythical causality provides interpretations for the situation, whereas causal ordering does not (comparative statics would provide means for stability analysis).

The influential work by de Kleer & Brown was the motivation for the development of a number of interactive learning environments. The two most important are QUEST (White & Frederiksen, 1990) and STEAMER (Hollan *et al.* 1984). These two systems will be examined below.

The notion of mental model is at the heart of QUEST (White & Frederiksen, 1990). QUEST makes use of interactive simulations, qualitative explanations and a troubleshooting expert. However, unlike SOPHIE and STEAMER, QUEST's pedagogical approach is based upon a progression of increasingly complex models that corresponds to the evolution of the learner's mental model.

White & Frederiksen argue that students should be first exposed to qualitative and causal models in order to make a connection with their naive intuitive models of physical phenomena. Quantitative reasoning should be introduced later, as a logical extension of the qualitative reasoning they acquired. In this approach, learning is viewed as a process of mental model transformation. The progression of models can be used for supporting tutorial actions and for student modelling. For example, when the student is at a certain level, the system can select questions the will induce the transition to the next level.

There are qualitative models of the circuit being simulated internally represented. They are implemented according to the component-based approach (de Kleer & Brown, 1984). Therefore, it is possible to derive causal explanations about the behaviour of the system by inspecting its structure. Explanations can be used for exploring the differences between the current and the subsequent models.

Another learning environment following the research line on mental models is STEAMER (Hollan *et al.*, 1984). This is a simulation-based environment, in which trainees can inspect a complex device (steam propulsion plants in large ships) and run simulations through a well developed graphical interface. The idea is that in exploring the learning environment, trainees could acquire a sophisticated mental model of the system, including a vast collection of procedures related to engineering principles.

Their pedagogical approach is that the simulation model presented to the learners should reflect more the mental model of experts about the system than the physical device itself (a principle called *conceptual fidelity*). In their view, conceptually faithful simulations can be considered a form of continuous explanations, since they reflect an expert's view of the phenomena.

As noted by Wenger (1987), STEAMER provides an inspectable abstract view of a quantitative model, but does not have mental models of the physical system it is trying to teach. Also it does not have means for generating causal explanations from the mathematical model, as SOPHIE and QUEST do. However, the whole project was concerned with providing explanations in qualitative terms. One of the members of the project, Ken Forbus, followed up with this line of research and developed the Qualitative Process Theory (QPT - see section 2.3), in which causality is explicitly represented.

2.4.2 Representing causality explicitly

Forbus & Gentner (1990) show that QPT, unlike the other two main approaches discussed in section 2.3, supports causal reasoning in two ways:

a) by means of an explicit representation of mechanisms that are the root of all changes (processes);
b) by using modelling primitives for expressing the direction of causation (direct influences and qualitative proportionalities).

In other words, only processes can cause changes, and these changes propagate from the directly influenced quantities to indirectly influenced quantities by means of unidirectional representations of causal relations: both I(A,B) and A α_Q B express 'B cause changes in A'.

For instance, how could one explain changes in the number of plants in a population? From the description of this problem in section 2.3, it is known that the immediate cause is an increment in growth rate, which is the direct influence on number of plants. Growth rate is in turn influenced by recruitment, and this depends on the number of seeds. Starting with the product of the *Seed_production* process (seeds), the chain of causality that results in the number of plants changing is expressed as follows

[recruitment] α_{Q+} [number_of(*Seed*)]
[growth_rate] α_{Q+} [recruitment]
I+ ([number_of (*Plant*)] , [growth_rate])

This approach contrasts with the component-based formalism. In the latter, changes arise as a consequence of the components interacting with other parts in the network, and the quantities are related by means of constraints. As mentioned above, mythical causality (or causal ordering) should be used to derive the implicit causal relations.

Forbus & Gentner (1986) sustain that the notion of *process* is central to human knowledge about physical situations, and therefore in mental models (of science). Thus, they defined the basis for a theoretical framework for learning about physical domains. Three key ideas underlie the theory: (a) the notion of process and the development of a *process vocabulary*; (b) the role of comparisons among related structures (analogy) in learning; and (c) the sequence from perceptual-based representations acquired earlier in the learning process towards sparse and abstracts representations of the domain. Based on these ideas, Forbus & Gentner propose a canonical learning sequence that corresponds to a sequence of different mental models of physical domains: (1) protohistories; (2) causal corpus; (3) naive physics; and (4) expert models.

Protohistories are contextually specific, highly perceptual representations of phenomena, capturing expectations about typical phenomenological patterns (for ex.: 'if turn the key, the car will start'). Next, with the *causal corpus*, the expectations of mechanism enter: there must exist something for the causal relation to happen, to cause the change (a process). However, the representation at this stage consists of simple statements that some sort of causal connections exists between variables (for ex.: 'if the car has no gas, it won't start'). In the subsequent stage, processes are introduced to provide the mechanism underlying the causal corpus. The disparate local connections of the causal corpus are replaced with qualitative models organised around the notion of processes (for ex.: 'gas must flow from the tank to the carburettor and mix with air so that the mixture can be ignited by the spark'). This is called *naive physics*. Finally, quantitative representations are created. At this level, the physical world is to be modelled as physical and mathematical models. These are the *expert models*. They have the advantage of being general models, which are close to the first principles (for ex.: 'models of the effects of different mixtures of oxygen and gasoline').

The process-based approach and its representation of causality have been related to the generation of causal explanations in a number of educational tools. For example, Forbus & Falkenhainer (1992) and Forbus (1993) describe an approach for integrating qualitative and quantitative models called self-explanatory simulations. A self-explanatory simulation combines the precision of numerical simulations with the explanatory power of qualitative representations. The idea is to use the qualitative analysis of a system as a framework for creating and organising a numerical simulator for that system.

Self-explanatory simulations are the basis for the development of new educational software, such as the Active Illustrations (Forbus, 1996). This architecture is a combination of self-explanatory simulators, visualisation tools and a coach, which is being used in science teaching at pre-college levels.

A different line of research is presented in Forbus & Whalley (1994). These authors describe the use of QR and other AI techniques in CyclePad, an environment for supporting students learning to analyse and design thermodynamics cycles, such as power plants and refrigerators. In CyclePad the occurrence of physical processes inside components is explicitly represented, and qualitative models are used for representing the limits on what is physically possible.

Making predictions is a crucial part of the explanatory interaction between students and learning environments. Rickel and Porter (1997) describe an interesting approach for answering questions using qualitative models. Given a prediction question and a library of model fragments, the answer is obtained in a two-step process. First a simulation model is created by selecting appropriate model fragments in the library. Then this model is used in a simulation that produces the predictions required by the question.

The domain chosen for their work is plant physiology. They used a large and multifunctional knowledge base (Porter *et al.*, 1988), and the compositional modelling technique (Falkenhainer & Forbus, 1991) for selecting the model fragments.

The main problem is to automatically generate the correct model for the simulation. If there are less details than the necessary, then the answer may be wrong. If there are irrelevant details, the simulation may become problematic and the answer difficult to understand.

There are two requirements for building the simulation model: a) the definition of what is relevant and what can be ignored for answering the question; and b) the determination of the adequate level of detail for the answer.

The former is achieved by selecting from the library things that happen from the same time scale of the phenomenon involved in the question. For example, the answer for a question about glucose production (minutes) can safely ignore the development of the root system (days).

The simplest level of detail adequate for answering a question is obtained by aggregating related processes. For example, the aggregated process 'photosynthesis' replaces all the intermediate steps in the process of glucose production.

Once the model is created, a simulation produces the predictions required by the answer. Their models are qualitative versions of differential equations. The question-answerer uses QPC (Crawford *et al.*, 1990) for compiling the model. As mentioned in section 2.3, QPC combines the QPT and QSIM. Therefore influences and proportionalities provide the necessary causal links between the quantities, and QSIM runs the simulations using the qualitative differential equations.

Selecting what to say and the level of detail to include in the answer are important issues for the generation of explanations. However there is another important aspect to be investigated: *how* to present the explanation?

2.4 3 Natural language explanations

There are at least two different approaches to generating natural language explanations. One is based on typical rhetorical structures of explanations, represented in so-called *schemata*, exemplified by TEXT (McKewon, 1985) and Pilkington & Grierson (1996). The second focuses on using planning formalisms that take into account intentions and beliefs to dynamically plan sequences of utterances to achieve certain communicative goals. This is the approach taken in KAMP (Appelt, 1985). Planning the general interaction with the user and dealing with interruptions during the dialogue was investigated by Cawsey (1991). This author shows that interactive explanations may be planned by using two levels of discourse planning: the content planning level (what to say) and the discourse planning (how to organise the dialogue and the interaction with the user).

A combination of schemata and planning techniques was used in the EUROHELP project in the DDP (Winkels, 1992). In this case, discourse strategies are planned on the basis of communicative goals, starting with a library of schemata called 'skeletal plans'.

Vadillo *et al.* (1997) took the DDP's approach for generating explanations from qualitative simulations in the context of training workers in an industrial domain. They follow the component-based formalism to explain the results obtained from differential equations simulation models. Domain knowledge is represented with multiple models, which constitute different views of the problems that can be used to support different types of explanations. Causal ordering is used for deriving causality from the system of equations.

Explanations are generated in three steps. First, the interaction type, the topic and the instructional task are selected. Second, an explanation plan (skeletal plan) is produced for each instructional task. This skeletal plan takes into account the cognitive model of the trainee and the history of the training session. The plan includes explanation strategies, the information piece to be presented. Finally, in the third step the actual explanation is generated. The most appropriated strategies are selected, and some actions associated with each strategy which implies the use of communication patterns contained in the strategy schema. The final message is completed with domain knowledge and knowledge coming from the simulation.

2.4.4 Cognitive diagnosis

An important requirement for generating explanations tailored to the student needs refers to the identification of the origin of the student difficulties. For instance, if a student gives a wrong answer during a problem solving activity, how can the tutoring system discover in which step of the reasoning process the student made a mistake?

Qualitative simulations can be useful for this task, as shown by Koning *et al.* (1997a; 1997b). These authors developed a mechanism for comparing the reasoning path followed by the students with a base model built upon a qualitative simulation. They took a model-based approach for the cognitive diagnosis. As mentioned in section 2.3, model-based reasoning is closely related to the component-based approach proposed by de Kleer & Brown (1984). Accordingly, for Koning *et al.* the topology of the 'device' is the network with *components* (inference steps) and *connections* (quantity values, derivatives and relations that are manipulated by the components) (Koning *et al.* 1997a). Note that they do not translate the reasoning steps made by the simulator, because this is different from the way humans reason. They used instead only the results of the simulation (facts) generated by the machine, and added all the inference steps connecting them based on observed human reasoning.

Koning *et al.* (1997a) describe a series of aggregation mechanisms to reduce the size of the network, and the result is that the aggregated network preserves the main steps of the problem solving and can be used for diagnosing students mistakes.

The first use of this approach in tutoring systems is in interpreting and diagnosing the reasoning behaviour of the student. When the student makes an error, this can be traced to some wrong inference step: the 'faulty' component is identified (Koning *et al*. 1997b). This approach has great potential for producing individualised explanations.

2.5 Conclusions

Building models for simulations and explanations in ecology requires representations and tools for reasoning with qualitative knowledge about quantities. There is a need for some sort of mathematics that allows for building general models and operating with qualitative values, both for magnitudes and for derivatives of the quantities. There is also a need for structured representations of ecological processes that can be used for grounding the generation of causal explanations about ecological systems.

QR can provide useful tools for ecological modelling. For the purposes of the work described in this thesis, the process-based approach seems more adequate. The conceptualisation of ecological systems as entities that change according to ecological processes is deeply inserted in the common-sense. Also this approach provides modelling constructs for encoding knowledge that can be useful for explanations, such as representations for the objects, situations and for the conditions under which the system changes. Causality is explicitly represented in QPT, and can be used for supporting causal explanations.

If QPT can be used for representing the dynamic aspects of ecological systems, the qualitative algebra developed in SIMAO can be used for the interpretation of these systems within a state. This algebra seems adequate for representing a large part of ecological data, and for building general models in the form of qualitative equations.

Chapter 3. The cerrado

Cerrado is a savana-like vegetation found in the central region of Brazil. It is currently under great pressure due to human occupation, farming, and excessive exploration of its natural resources. Conservation practices are urgently required and education has a role to play in achieving this. This is one of the motivations of the present work.

This chapter is concerned with describing the nature of cerrado vegetation and the process of acquiring knowledge about it. A summary of the acquired knowledge is further provided. In section 3.1 the area studied is described. The techniques used for the acquisition of knowledge are discussed in section 3.2. An overview of the knowledge acquired is presented in section 3.3. Finally, section 3.4 brings some topics that should be part of a curriculum concerned with educating students about cerrado vegetation dynamics and might be represented in qualitative models, according to the opinion of the author.

3.1 Characterisation of the studied area

Cerrado is characterised as a tropical savanna because of the presence of an almost continuous and well developed grass layer, and a discontinuous layer of trees and shrubs. It covers almost two million square kilometres in the central region of Brazil. In this area the climate is tropical with a well marked dry season between May and September, and a wet season between October and April. The average annual rainfall ranges between 1100 and 1600 mm, 90% of which falls during the wet season.

The cerrado vegetation holds great biological diversity and consists of many natural communities. These communities are well defined groups of species that occur together (physiognomies). In fact, according to Eiten (1982), cerrado is one of the few large-scale vegetation types in the world with so many different natural physiognomies.

Cerrado communities vary from open grasslands to closed forests, and have been studied by several researchers (for example, Goodland & Ferri (1979); Eiten (1972;

1982); Coutinho (1990); Moreira (1992)). This thesis focus on five types of communities, called *campo limpo*, *campo sujo*, *campo cerrado*, *cerrado sensu stricto* and *cerradão*[4]. These communities can be organised in a gradient of successional stages according to the quantities of trees, shrubs, herbaceous and grass in each community, as shown in Figure 3.1:

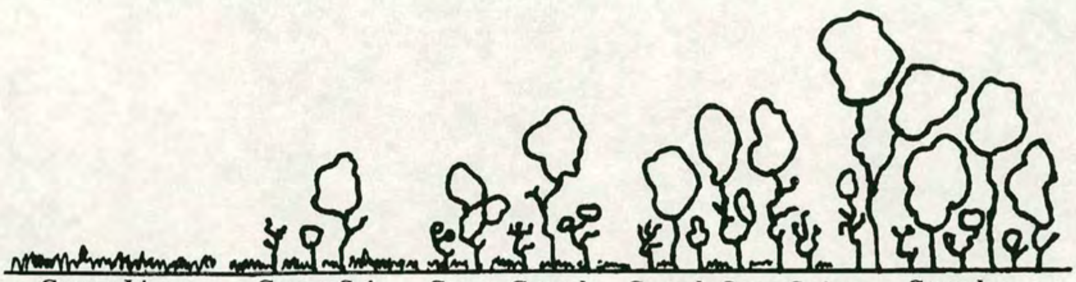

Figure 3.1 Gradient of communities in the cerrado.

Two main groups of plants can be identified in cerrado communities, according to their behaviour: {trees/shrubs} and {herbaceous/grass}. The latter are not purely shade-tolerant nor purely shade-dependent, as one would expect from the fact that they are mixed in the intermediate types of communities in the gradient above (Coutinho, 1990). There is a clear negative relationship between the two groups along this gradient. For example, the quantity of {trees/shrubs} is much bigger than {herbaceous/grass} in cerradão, and the contrary in campo sujo and campo limpo (see Goodland & Ferri, 1979, for a detailed study of this gradient). Coutinho (1978; 1990) considers that there are two main types of ecosystems at the extremes (campo limpo

[4]The names of the cerrado communities will be quoted in Portuguese throughout the thesis. Some communities were not included in this study (e.g. certain types of forests and very humid areas called 'veredas').

and cerradão), and the other communities are intermediate ecotones. More details about the cerrado will be provided in section 3.3.

Near Brasília, the Brazilian capital, there is a number of ecological reserves. The University of Brasília has been responsible for most of the studies on the ecology of cerrado during the last 30 years. As a result, an extensive and comprehensive literature about the cerrado has been produced in the form of research papers, articles, books and MSc theses.

Currently the Department of Ecology of the University of Brasília is involved in the 'Projeto Fogo' (the Fire Project), along with other Brazilian and international organisations. The objective of this project is the assessment of the effects of fire on the vegetation under different conditions, and the possibility of using fire as a management tool. The area of study for the 'Projeto Fogo' is the Ecological Reserve of the Brazilian Institute of Geography and Statistics (IBGE), and some of the results of their research have been published recently (see Miranda *et al.*, 1996).

Knowledge for the research described in this thesis was obtained from the researchers involved in the Projeto Fogo. This was a natural option, given the concentration of researchers working in the same topic, in an area that has been extensively studied and reported in the literature.

3.2 Knowledge acquisition

Relevant knowledge for the work described here involves a theory about the mechanisms underlying the behaviour of cerrado communities, and means by which this knowledge can be communicated to students. In a broad sense, it includes scientific knowledge used by researchers, and some heuristics based on the personal experience of teachers.

The techniques for knowledge acquisition used in this work included a review in the literature, and interviews with researchers involved in the 'Projeto Fogo'. The personal experience of the author, and direct observation of the area of study, were also important for the organisation of the domain knowledge.

An extensive literature review was carried out to obtain background information on the following topics:

a) the effects of fire on plant populations

b) the structure and dynamics of cerrado communities

Acquiring knowledge from experts tends to be a difficult task. It involves not only factual information, but also capturing intuitions and implicit knowledge. Kuipers & Kassirer (1987), describing the process of knowledge acquisition for building qualitative models, noted that experts have a causal model of their domain of knowledge which supports their performance, and this knowledge is compiled in such a way that a long chain of inferences is likely to be reduced to a single association. In the context of this research, these problems were minimised because the author is also an ecologist and teacher, being therefore able to share the same thought processes with the experts.

The technique used for acquiring knowledge from the experts was a mix of unstructured and focused interviews. The preparation involved some background reading in the area of expertise of the interviewee, and some planning about what to ask and typical problem-solving activities they could do during the interview. Most of these researchers are also experienced teachers. Therefore they could provide information about scientific knowledge in their area of expertise, while suggesting what to include in the curriculum, and how to communicate their knowledge to students.

A preliminary exercise in knowledge acquisition and representation was done by interviewing Dr. Colin Legg from the Institute of Ecology and Resources Management (IERM) - University of Edinburgh, on 12/10/95. Knowledge about the behaviour of plants from the genus *Calluna* acquired in this interview was encoded in a simple rule-based system. This knowledge base was used to generate explanations in a similar way to that described in Salles *et al.* (1996), using a shell described in Bratko (1990). This prepared the author for subsequent work in Brazil, and demonstrated the feasibility of representing and reasoning with knowledge acquired in this way.

The full knowledge acquisition work was undertaken during a visit to Brasília, between November 1995 and January 1996. The following table (Table 3.1) presents the researchers interviewed during this period[5]:

name	institution	domain	position
Augusto Cesar Franco	UnB	eco-physiology	researcher / lecturer
Bráulio F. S. Dias	UnB	biodiversity	researcher / lecturer
Carlos Klink	UnB	ecology of Grammineae	researcher / lecturer
George Eiten	UnB	botany	researcher / lecturer
Heloisa S. Miranda	UnB	ecological modelling	researcher / lecturer
Jeanine Maria Felfili	UnB	ecology of communities	researcher / lecturer
John D. Hay	UnB	population ecology	researcher / lecturer
Leopoldo M. Coutinho	USP	ecology of communities	researcher / lecturer
Linda S. Caldas	UnB	eco-physiology	researcher / lecturer
Manoel C. da Silva Jr.	UnB	ecology of communities	researcher / lecturer
Margarete Naomi Sato	UnB	population ecology	MSc student
Mercedes Bustamante	UnB	soils and nutrient cycles	researcher / lecturer
Raimundo P.B. Henriques	UnB	ecology of communities	researcher / lecturer
Saulo M. de A. Andrade	UnB	population ecology	MSc student
Vânia Pivello	USP	knowledge based systems	researcher / lecturer

Table 3.1 Researchers interviewed for this thesis.
UnB: University of Brasília; USP: University of São Paulo

The interviews with Brazilian researchers were one and half hour on average, and consisted of two parts. The first part was an informal conversation. The experts would talk almost freely about general issues they considered relevant. During this period, the author made few comments and asked some general questions. During the second part of the interview, the experts were asked to talk more about some ecological processes, to generate lower level information, and to mentally run simulations about what could happen in hypothetical situations. Some details were further explored, with questions

[5]The researchers V. Pivello and L. M. Coutinho, from USP, are not directly involved in the 'Projeto Fogo'.

about clarifications, quantizations, causal relations. Finally, some questions about the educational aspects of their work were made. These questions referred to the curriculum, pedagogical methodologies and the most difficult aspects to be communicated, for both teacher and students.

The conversations were taped and used later for further studies about the main problems and the causal reasoning involved in the problems mentioned during the interview. On a number of occasions, a second interview was undertaken, in order to clarify some points.

The focus of the interviews was on the qualitative knowledge about the domain used by the expert. Relevant concepts used for representing and reasoning about the domain and the theoretical basis for their studies were explored. Whenever possible, the expert-teacher was asked about how these concepts could be included in the curriculum and communicated to the students.

3.3 The knowledge acquired

This section presents an overview of the main aspects of the ecology of the cerrado identified in the literature review and in the interviews with the Brazilian researchers. This is not an extensive review of the problems. It is rather a guideline for the selection of the domain knowledge to be encoded in the qualitative models.

As mentioned in section 3.1, the cerrado is characterised by the occurrence of different types of community, classified according to the quantities of trees, shrubs, herbaceous plants and grasses. However, the spatial distribution of these types of communities is far from homogeneous. In fact, the cerrado can be seen as a mosaic of communities. Very different types of community (such as cerradao and campo sujo) can be found side-by-side. So, what are the main ecological factors determining the type of vegetation in a certain area?

The structure of the vegetation is determined by the effects of five factors: soil nutrient availability, soil moisture availability, herbivory, fire, and human actions (see Moreira, 1992). Availability of nutrients and water in the soil are the primary determinants. The former is an issue because the soil in the cerrado region is poor in nutrients. The latter is a limiting factor during the dry season. Water availability depends on the depth of the water table, and for how long a satisfactory level can be maintained during the year. These soil characteristics associated with the type of community are for example, if the soil is rich and deep, then the community is on the cerradão side of the gradient[6].

While herbivory does not have a great impact on the dynamics of the cerrado (Bráulio Dias, pers. comm.), fire is an important influence on the vegetation. Fire is an ancient factor in the ecology of the cerrado. There are records of fire more than 20.000 years before the present (Coutinho, 1990). Lightning is the main natural cause of fire in the cerrado, but overall human actions are the main cause of fire. It can be used as a management tool by farmers and traditional populations. The Kayapó Indians, for example, use controlled fire for stimulating fruit production in some species, and avoid burning when sensitive species are in their reproductive period (Posey, 1986). In the last 40 years, the impact of human actions on the cerrado increased with the occupation of the central region of Brazil. As a consequence, the cerrado has been burned with increasing frequency.

Fire has positive and negative effects on the ecosystem (see Coutinho, 1982; 1990 and Frost & Robertson, 1987, for a general overview of the effects of fire on the cerrado). Among the most relevant abiotic effects, it is accepted that fire alters energy, nutrient and water fluxes between soil, plants and atmosphere. Research has concentrated on the micro-environment near the ground level and on the plants. For example,

a) *Air temperature*. During the fire event, the air temperature initially increases, and then decreases. Given that grass, leaves and small pieces of wood are the most important components of fuel in the cerrado, in general the fire event is brief, and high

---

[6]According to Braulio Dias (per. comm.), this classification is useful for didactic purposes. However, there is some evidence that intermediate communities can be found in areas with fertile and deep soils.

temperatures do not last for long periods (Miranda *et al.*, 1993). Weak winds, plane topography and the discontinuity of canopy also contribute to the moderate propagation of fires.

b) *Soil temperature*. Miranda *et al.* (1993) noticed that, at 2 cm depth, maximum soil temperatures ranged from 29 °C - 38 °C. At 5 cm depth, changes in soil temperatures were negligible. The main reason for that is the low quantity of organic matter in cerrado soil. Consequently, fire does not cause much damage to the underground parts of plants.

c) *Nutrient cycling*. After burning, many types of nutrients at the soil surface increase. Herbaceous plants play an important role in the rapid and efficient nutrient cycling, because of their superficial root system. There is also an inflow and outflow of nutrients through the atmosphere. It is assumed that, if fire is not too frequent, there is an equilibrium for most nutrients. However, fire is now becoming too frequent, breaking this balance (see for example, Kauffman *et al.*, 1994). There is also a risk of increased soil loss from an area laid bare by fire, which is a major concern in cerrado management. Since soil nutrients are concentrated on the soil surface, erosion may result in a significant depletion of soil nutrients, as well as in a reduction of soil depth and water holding capacity.

In natural conditions, fire events are predictable seasonal events, which results in adaptation of the vegetation. As a result of this adaptative process, morphological protective features are common in cerrado species, such as the strong suberization of trees (protective tissues) and the protection of dormant apical buds.

Fire may have positive effects on the vegetation. For example, Coutinho (1990) discusses the effects of fire on flower production, dispersal of fruits and seeds, and germination. Data about the fauna are scarce, but it seems that animals benefit from the increase in food and minerals after burning and from the resprouting of many species.

Certainly fire may kill individual organisms, modify the growth and reproductive rates in some populations, and cause changes in the relationships between organisms (e.g. competition). However, fire frequency is more relevant for these changes than the intensity of isolated fire events. For example, given the characteristics of the fire in cerrado described above, the mortality of cerrado plants does not increase significantly after fire events (see, for example, Rocha-Silva & Miranda, 1995), provided that the fire frequency is not too high and the vegetation has time enough to recover from the previous fire event.

Biomass of the cerrado plants below ground is much greater than above ground. Given that temperatures underground do not change significantly during a fire event, cerrado plants are reasonable protected. Even if their above-ground parts are completely destroyed (something that often happens, because most fires occur during the dry season), they survive and resprout. Many woody plants have mechanisms of resprouting from bulbs, rhizomes, and xylopodia (Rawitscher & Rachid, 1946).This is a very important reproductive mechanism in cerrado plants. Shortly after burning it is common to find young plants that have been produced by asexual reproduction.

In the long term, these effects may result in changes in the population structure of some species, and in the composition of species of communities. For example, the diversity of species in protected areas increases. There is an invasion of species sensitive to fire brought by animals from the cerradão (Braulio Dias, pers. comm.).

If fire frequency is high, the vegetation becomes open, with more grass and less trees, and changes towards the campo limpo side of the gradient. The differences in the behaviour of trees and grass under the influence of fire is a long time's standing problem (Carlos Klink, pers. comm.): it is accepted that fire is a negative influence for trees and positive for grass.

This situation involves a positive feedback loop. The main components of the fuel in cerrado are grass leaves and small pieces of wood (Heloisa Miranda, pers. comm.). Communities such as the campo limpo and campo sujo (Figure 3.1) are rich in these components. Thus, increased fire frequency creates conditions for fire to become more frequent.

An important issue in the discussions with the experts was the succession of cerrado communities. It is widely accepted that the communities shown in Figure 3.1 can be seen as different successional stages of the vegetation, and the climax is the cerradão. Therefore in ideal conditions, a protected area of cerrado tends to become a cerradão. This is a very idealised supposition, but it can be seen as the basis for the common-sense theories about the dynamics of the vegetation. It may also be useful for educational purposes.

Cerrado is nowadays under great pressure due to farming and human occupation. Conservation practices are urgently required. Large areas of natural vegetation are being destroyed and replaced by big farms and huge fields of soya beans. These changes are causing several social and ecological problems. Peasants and small farmers are leaving their land, and production of some traditional crops is decreasing. The destruction of the cerrado also represents loss of biodiversity and genetic resources in species of plants traditionally used as medicine or as raw material, and undoubtedly many unknown species.

It is widely accepted that any strategy for conservation involves education. This is one of the main motivations for the present work. There are many elements that justify the development of computer-based educational tools to be used in Brazilian secondary schools and universities located in cerrado areas. For example,

a) there is a high flow of students coupled with low availability of instructors;

b) 'learning by doing' may be more effective than 'learning by being told';

c) field work can be supplemented or even replaced by computer-based tools;

d) experiments and simulations with real ecosystems are, in general, impossible to carry out.

3.4 What should be taught about the effects of fire on the cerrado?

This section presents educational objectives to be achieved with the qualitative models developed in this thesis. The objectives are organised around topics of domain knowledge, identified during the process of knowledge acquisition. These objectives reflect the opinion of the author, based on the interviews with the expert-teachers, the literature review, and on his own experience. Along with the objectives, additional bibliographical references are presented. These are not meant to be extensive, but point for the nature of the knowledge that should be explored along with the qualitative models.

Flowering

Concerning to flowering, the models should

> demonstrate the effects of fire and other environmental factors on the flower production in cerrado plants;
>
> support comparative studies about the behaviour of different species in response to fire.

Additional literature: Silva *et al.* (1996); Salles (1988); Murakami & Klink (1996).

Fruit and seed production

With respect to the process of seed and fruit production, the models should

> illustrate the effects of fire on fruit and seed production in different species of cerrado plants;
>
> describe the importance of pollinator insects for the production of fruits and seeds in cerrado plants.

Additional literature: Salles (1988); Oliveira & Silva (1993).

Germination

Models about germination should

describe the influence of environmental factors such as fire, light, temperature, soil water on the germination of seeds in cerrado plants;

support comparative studies about the behaviour of different cerrado plants under the influence of the above mentioned factors.

Additional literature: Felippe & Silva (1984); Oliveira & Silva (1993).

Establishment

With respect to establishment, the models should

represent the influences of fire, temperature, soil water and other environmental factors on the establishment of cerrado plants;

explore the different behaviour of cerrado plants with respect to their response to the above mentioned factors.

Additional literature: Franco *et al.* (1996); Hoffmann (1996); Oliveira & Silva (1993).

Mortality

The models about mortality should

illustrate the effects of fire and other environmental factors on the mortality of cerrado plants;

support comparative studies about the mortality in cerrado plants.

Additional literature: Raw & Hay (1985); Silva, Sato & Miranda (1996); Sato & Miranda (1996).

Colonisation

The models should

represent the importance of colonisation for the succession in cerrado.

Additional literature: Coutinho (1977); Sato & Miranda & Klink (1996).

Communities

Models about communities should

describe the characteristics of the cerrado communities;

support comparative studies about the components of the cerrado communities.

Succession

Models about succession should

illustrate theories about the causes of succession in cerrado communities;

represent influences from fire, litter, soil water and other environmental factors on the succession of cerrado communities.

Additional literature: Goodland & Ferri (1979); Moreira (1992); Pivello (1992); Pivello & Coutinho (1995)

Fire and environmental factors

Models about fire and environmental factors should

illustrate the importance of fire for the dynamics of the vegetation in the cerrado;

support comparative studies about the behaviour of different communities influenced by fire;

explore the importance of different components of the vegetation for the fuel dynamics in the cerrado.

Additional literature: Miranda *et al.* (1993); Ramos-Neto & Pinheiro-Machado (1996); Neves & Miranda (1996); Dias, Miranda & Miranda (1996); Miranda, Silva & Miranda (1996); Kauffmann *et al.* (1994).

General

The models should

present an overview of the characteristics of the cerrado vegetation.

Additional literature: Warming (1973).

3.5 Conclusions

Interviews with Brazilian researchers, review of the literature, and direct observation of the area of study provided the ecological knowledge necessary for the development of the work described in this thesis. Since most of the interviewees are also teachers, it was possible to have an overall idea of relevant educational problems related to the communication of ecological knowledge about the cerrado for undergraduate students.

This knowledge was useful for the definition of educational objectives to be achieved by using qualitative models.

Chapter 4. Modelling qualitative ecological knowledge for educational purposes

A *model* is a description of a system. A *system* is a collection of interrelated objects. An *object* is some elemental unit upon which observations can be made but whose internal structure either does not exist or is ignored (Haefner, 1996). Systems can consist of subsystems, which in turn are collections of objects.

Models are built for many different purposes. The models described in this thesis were developed to support both simulations and explanations about ecological systems in learning environments. Simulation involves the calculation of quantity values, given knowledge about the constraints between these quantities and a description of the initial scenario. Explanation involves tracing the simulation to show *how* the values were calculated, and combining pieces of domain knowledge to say *why* the calculations have been done and *what* happened to the system.

In this chapter, a general framework for building qualitative models is defined. It starts with a theory about qualitative ecological knowledge, followed by a discussion about what to say in these models, the language used to say it, ending with guidelines on how to implement such models.

In order to represent relevant knowledge about the ecology of fire in the Brazilian cerrado vegetation, a qualitative theory of vegetation dynamics is developed in section 4.1 from the ecological studies discussed in Chapter 3. This theory assumes that population is the basis for representations of the vegetation. Variation in population size is grounded on natality, mortality, immigration and emigration. These processes may in turn include other physiological processes and may be influenced by environmental factors.

For the sake of clarity, when discussing the models and the modelling process, a framework is proposed in section 4.2 which distinguishes the main concepts used for describing the system being modelled, the causal relations between the model components, and the mathematical operations required for calculating the value of the quantities.

The modelling languages used for implementing the models, QPT and SIMAO (see Chapter 2), are presented in relation to this framework in section 4.3 and 4.4. QPT can describe concepts and causal relations, but cannot provide a detailed representation of mathematical operations. SIMAO, in turn, has a useful qualitative algebra, but lacks primitives for representing concepts. Combined, QPT and SIMAO offer a powerful set of modelling primitives for building models that can support both simulations and explanations.

The modelling process has been recognised as an issue in itself, among researchers in both ecological modelling (e.g. Muetzelfeldt, 1991) and qualitative reasoning (e.g. Schut & Bredeweg, 1996). The work described in this thesis offers an opportunity for exploring the task of building qualitative models in its different stages. Some guidelines for identifying organising concepts, building the libraries, and controlling the simulations are discussed in section 4.5. The content of this section is partially presented in Salles & Bredeweg (1997).

4.1 Towards a qualitative theory of vegetation dynamics

A theory is a set of ideas that explains and supports predictions about something in the world. A *domain theory* (Falkenhainer & Forbus, 1991) is a representation of the knowledge about some domain in qualitative modelling. It describes in qualitative terms what kinds of entities and phenomena can occur in a particular domain.

This section presents a domain theory about vegetation dynamics. Given that populations have been recognised as the basis for studies about vegetation (Harper, 1977), the domain theory proposed here is a qualitative theory of population dynamics.

The fundamental question to be answered in any model about population dynamics is 'what is the size of the population at a certain time?'. Answering this question is the motivation for building both quantitative and qualitative models. Not surprisingly, the domain theory outlined in this section starts with a qualitative representation of the most basic equation used to describe the behaviour of the population in mathematical models (section 4.1.1). This point is expanded in the following section (4.1.2), with a discussion about the importance of the basic processes in determining the size of a population. Each of these basic processes in turn can include other physiological processes (section 4.1.3). Thus the basic processes may have different representations in qualitative models, in order to accommodate the particulars of the different species. Environmental changes are largely responsible for changes in populations. How to incorporate them into qualitative models is discussed in section 4.1.4. Finally, the domain theory about populations presented here can be used to support models of communities and ecosystems. Possible extensions for the domain theory are discussed in section 4.1.5. The actual libraries of model fragments are presented in Chapters 5 and 6.

4.1.1 Population growth: the fundamental problem of vegetation dynamics

The notion of 'vegetation' is associated with groups of plants of different species living in a certain area. For example, in the phrase 'the cerrado changes', it is implicit that one or more groups of grass, herbaceous, trees in the cerrado vegetation are changing. These groups can be represented as populations. The principles of population dynamics can be seen as the first principles for ecological studies[7] about vegetation dynamics. A domain theory about the dynamics of the vegetation must be therefore a theory about populations.

The most typical utterance about populations is something like

(s.4.1) 'The population is small and is increasing.'

[7] I thank Takashi Washio for interesting discussion about first principles in physical systems, and their correspondent in ecology.

This phrase has two components that entail different aspects of a domain theory about populations. The first is the notion of magnitude of the population size, represented by the value ‘small’. It is a reference to how big the population is, and is useful for comparison with other populations. The second is the direction of change in the population size over time, represented by the value ‘increasing’. It is a direct reference to the dynamics of the population, and is useful for predicting the size of the population in the future.

A description of how population size changes can be formulated as follows:

> (s.4.2) ‘The number of individuals at a certain time is the number at the previous time modified by the net variation in the whole population during this time interval.’

The basic (qualitative) equation[8] to implement this statement is

$$N_{t+1} = N_t + \Delta N \qquad (1)$$

This equation states that the number of the individuals at time t+1 (N_{t+1}) can be calculated from the number of individuals at the time t (N_t) and gives some measure of the variation within the time period. A quantity (ΔN) is introduced to represent variation. This term ΔN represents the net amount of individuals added to or removed from the population, during the time interval between t and t+1 (Δt).

The statement (s.4.2) can be rephrased as N_t = small , ΔN = increasing and thus N_{t+1} will be some magnitude greater than ‘small’. This rationale is actually the core of any method for calculation of changes in the population size, and must be at the heart of a qualitative theory of population dynamics.

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[8] The operators (+) and (−) are used in this section for expressing qualitative addition and subtraction, and the symbol (=) for equality.

Naturally, in this domain theory, all the components of this model should be expressed in qualitative terms. Some representation of the magnitudes in qualitative terms may exist, for example {small, large}, as well as some sort of qualitative mathematics combining them but this is not absolutely necessary. Many interesting conclusions about the behaviour of the system can be derived from representations of the direction of change only (for example, see de Kleer & Brown, 1984). In the models we are discussing, direction of change is represented by ΔN. Assuming that it can take on values {negative, zero, positive}, equation (1) describes qualitatively the three possible behaviours during a certain time interval:

a) the population is increasing when ΔN is positive, and therefore $N_{t+1} > N_t$;
b) the population is stable when ΔN is zero, and therefore $N_{t+1} = N_t$;
c) the population is decreasing when ΔN is negative and then $N_{t+1} < N_t$.

In the next section, the determinants of population behaviour are identified.

4.1.2 The basic processes affecting the population

The behaviour of a population reflects the final result of its interaction with a certain environment. But what is in this interaction?

> (s.4.3) There are only four biological mechanisms that directly cause changes in the population size: natality, mortality, immigration, and emigration.

They represent, respectively, individuals being born (B), dying (D), immigrating (I), and emigrating (E). Accordingly, variation in the population during a time interval Δt can be expressed as

$$\Delta N = (B + I) - (D + E) \qquad (2)$$

Equation (1) then becomes

$$N_{t+1} = N_t + (B + I) - (D + E) \qquad (3)$$

All the terms in equation (3) have clear meaning, and the constraints between them are also very clear. The qualitative interpretation of this equation is straightforward and easy to communicate to students. For example, when (B+I) > (D+E), then $\Delta N > 0$, and the population is increasing. This model represents open populations, because I and E are included. Removing these terms from the equation will result in a model for closed populations.

This notion of variation (ΔN) over time can be represented in different ways. Time can be seen as either a succession of discrete intervals (for example, one year), or a continuous variable, depending on the characteristics of the population being considered and the purposes of the model. For example, if we want to know what is happening to the population now, it is necessary to have the instantaneous variation. In differential equation models, this is represented[9] as dN/dt (almost all the textbooks about population ecology discuss these models; for example Gillman & Hails, 1997).

Two types of quantities can be recognised, according to their importance for describing the system's behaviour. In the equations (1) - (3), the focus of attention is on the number of individuals. This is the most important quantity describing the system under consideration, and the only quantity for which variation is explicitly calculated and represented (see statement s.4.1). The quantities B, I, D, and E are included because their magnitude is necessary for calculating the variation of the number of plants. There are no representations of the variation of these quantities, although all of them may be changing.

However, this is not the only possible approach for capturing qualitatively the dynamics of the population. If the variation in the auxiliary quantities is known, it may be possible to determine the variation in the number of plants. For instance, if B and I

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[9]Two models of this kind presented in almost all textbooks are $dN/dt = rN$ for representing unconstrained growth, and $dN/dt = rN\,(1 - N/K)$, for density dependent populations.

are increasing and D and E are decreasing, there is no doubt that the population is increasing. In some cases the final result may be ambiguous: for example B and D are increasing, while I and E are decreasing. Information about the magnitudes of the quantities can be used to solve the ambiguity.

The knowledge discussed so far not only describes how to proceed with the calculations, but also may support explanations about *how* the values of the quantities are calculated in learning environments. Though some model components are explicitly represented, it is still not possible to say *why* calculations have been done. There are no explicit references to concepts related to the plants themselves, or to the conditions for things to happen. Also implicit are the causal relations involving the environmental factors that might be influencing the population. How to incorporate them in the domain theory is discussed in the next section.

4.1.3 Introducing other components in to the models

A qualitative theory of population dynamics should allow for different perspectives on the fundamental problem of how to represent changes in population size. The importance of natality, mortality, emigration and immigration for the final outcome of the number of individuals in the population is clearly defined. However, each of these processes encodes details that may be important for representing the differences between the organisms, and how they respond to the environment.

For example, natality may involve the production of flowers, fruits, seeds, germination, establishment, and sexual reproduction. Each of these components is a complex ecological process in itself, and may sometimes be explored in detail. To be consistent, the domain theory has to establish the link between the basic population process and their physiological components. Thus it can support utterances such as

> (s.4.4) 'Flowering is part of the mechanism that results in the production of new plants.'

Environmental factors may influence the dynamics of the vegetation through these components. For example, the effects of fire on the natality in plants may have different interpretations.

For some plants, the most sensitive stage is the germination of seeds, whereas for other plants, it may be the production of flowers:

(s.4.5) 'Fire affects the population by influencing flowering.'

The statements (s.4.4) and (s.4.5) show that, in any case, the link between the environment and the population may be clearly established by means of references to the basic processes. This is an important achievement in order to keep the coherency in the domain theory.

If it is assumed that fire is the only influence on the population, then it is possible to represent the effects of fire by adding a quantity (F) to the equation (3). This equation may become an expression such as

$$N_{t+1} = N_t + ((F * B) + I) - (D + E) \qquad (4)$$

Equation (4) is a possible formalization of the statement (s.4.5), in which the influence of fire on natality is represented by the product between the two quantities (F * B). There is a number of points to be discussed about this equation:

1)The equality (=) between the two sides of the equation implicitly assumes that all the factors necessary to calculate N_{t+1} are known and included in the equation[10]. As mentioned above, fire is the only factor (apart from the basic processes). However, there is always a huge number of simultaneous influences to be considered. An important feature of QR representations is making the assumptions explicit. Thus if it

[10] This is not an issue in equation (3), because it represents all the biological components of population change.

is assumed that all the influences are known, qualitative equations such as (4) may be written. If we are not certain about the influences, then a different type of qualitative equation is required.

2) Equation (4) does not express the causal relations between the modelling elements. It has been said that fire influences flowering (statement s.4.5), and this is captured by the term (F * B). However this is not explicit: there is nothing in the equation saying that F causes changes on B, and not the contrary. A representation for causality is required, particularly because one may want to introduce influences on the influences themselves.

3) This model also does not express the conditions for things to happen. For example, is there a minimum amount of heat for the influence of fire on flowering to be significative? The answer cannot be derived from the model (as it is) to be used in explanations, because the conditions for it to hold are not explicit.

4) The quantities involved in the equations (1) - (3) refer to the same object, namely the population of plants. In equation (4), a quantity (F) represents a different object introduced in the model, namely the cerrado, where population is located. Given that the quantities are not related to any other modelling component, it is not possible to derive from the model itself what the objects involved are. This is an important piece of knowledge for grounding the explanation.

These four points mentioned above shed some light on future extensions of the domain theory of population dynamics. They are expanded further in section 4.2.

4.1.4 Possible extensions for a qualitative theory of population dynamics

The domain theory about populations outlined in the previous sections has two properties. Firstly, it is general enough to be applied to different types of organisms (for example, animals). Secondly, it represents the 'first principles' for reasoning about ecological systems. Therefore it has the potential for supporting the development of theories about more complex categories of biological systems, such as communities and ecosystems.

Communities are groups of populations living in a certain area, during a certain time period. According to this point of view,

(s.4.6) 'Changes in communities are fundamentally changes in populations.'

The simplest representation for communities in qualitative modelling is obtained by combining single models about populations. For example, communities in the cerrado may be represented by combinations of populations of trees, shrubs, herbaceous and grass. Succession of communities can be captured this way. However, a theory about communities has to deal with emergent properties that do not exist in populations. For instance, the diversity of species is a property of communities that makes no sense at the population level.

Less straightforward but still possible is the extension of domain theories about populations and communities for theories about the ecosystem. Ecosystem is a higher category in the organisation of biological systems, representing the interaction between the community and the physical environment. A domain theory in which environmental factors are associated with the calculation of the size of the population through the basic processes of natality, mortality, immigration and emigration might be applicable to theories about ecosystems.

Section 4.1 can be seen as the starting point towards a qualitative theory of vegetation dynamics. The next section discusses what should be included in this domain theory in order to produce a more complete representation of ecological systems in qualitative models.

4.2 What to say? Representing the structure and the behaviour of the system in qualitative models

A framework for building qualitative models is proposed in this section. It is assumed that, in order to support both simulations and explanations about the structure and the behaviour of ecological systems in learning environments, three aspects have to be explicitly represented in qualitative models:

a) the main concepts that constitute the domain knowledge being communicated;
b) the causal relations between the model components;
c) the mathematical operations required to calculate the value of the quantities.

This framework postulates that the physical structure of the system can be decomposed in three components, corresponding to the three aspects mentioned above. These three components are presented in section 4.2.1, and developed in the following sections. Each section is a tentative answer to a question about the modelling process. The questions are: What are the elements being modelled in the system? (section 4.2.2); How are these elements characterised? (section 4.2.3); How are they related? (section 4.2.4); What are the situations that provide good descriptions of the system? (section 4.2.5); What causes change in the system? (section 4.2.6); Finally the use of simpler models to build more complex representations of the system is discussed in section 4.2.7.

4.2.1 A general framework for knowledge representation in qualitative models

A framework for building qualitative models which can be used for supporting both simulations and explanations in learning environments is proposed in this section. In this framework,

> (s.4.7) 'The physical structure of a system can be decomposed in three components: the conceptual structure, the causal structure, and the mathematical structure'.

This framework is useful in helping one to think about the models and the modelling process, and for organising the presentation of the models implemented. Each component is associated with a certain type of knowledge, and has a certain function in qualitative modelling. They can be defined as follows:

a) The *conceptual structure* includes the main concepts used for describing the physical structure of ecological systems (see section 4.1.3). This component involves concepts related to the objects, their relevant properties (for the purposes of the model), and quantities used for representing these properties. An important part of the conceptual structure refers to the relations between quantities. These relations provide links between the objects in the system. They are therefore important concepts to be learned about the domain.

The conceptual structure includes descriptions of typical situations in which the system or its components are involved. These descriptions must specify the conditions for the situations to appear. Moreover, concepts related to the mechanisms of change are part of the conceptual structure. The conditions for changes to start and to stop as well as the modifications they introduce to the system must be explicitly represented. These notions of situations changing under the effects of ecological mechanisms and events have great importance for understanding the system's dynamics.

From the definition above, it can be argued that the conceptual structure includes almost everything we want the students to learn about ecological systems. This has to be like that, because ultimately we want the students to learn concepts. There is always some sort of conceptual structure of the type described here in the modeller's head, irrespective of the modelling framework applied. However, in models designed to communicate knowledge to students, this conceptual structure must be explicit: it is essential for formulating explanations. How to make it explicit is the topic of several sections of this chapter.

b) The *causal structure* can be compared to a network of nodes representing quantities, and arcs representing the causal relationships. In this network, there are indications of points where changes could start, and of which quantities are causing changes in other quantities. By inspecting this structure, the student would be able to understand how causality flows within the system.

The causal structure may be hidden from the student, but it is essential for explanations (referred to as causal explanations). A sequence of examples will show how explanations can be improved if they are based on this causal structure. Initially, suppose there is no representation of the causal structure. Explanations in this case would refer to simple lists of changing quantities, for example

> (s.4.8) 'The quantities amount of nectar, number of pollinated flowers, and number of insects changed their values'.

Such lists may not be enough for the student to understand what is happening with the system. This is particularly true if the system is complex and there are several quantities involved. Understanding is more likely to be achieved if the student can see how the quantities are related, for example, in phrases such as

> (s.4.9) 'Changes in the amount of nectar cause changes in the number of insects, and this in turn causes changes in the number of pollinated flowers'.

It would be even better if the distinction between primary causes of change and secondary causes of change can be made. This would allow for explanations such as

> (s.4.10) 'When the number of flowers change, the amount of nectar also changes. Changes in the amount of nectar cause changes in the number of insects, and this causes changes in the number of pollinated flowers'.

Explanations like (s.4.9) and (s.4.10) are supported by the causal structure. Combined with the conceptual structure, more complete explanations about the system's behaviour may be formulated. For example, if knowledge about the conditions for changes to happen is added, then it is possible to say

> (s.4.11) 'Flowering in plants of the genus *Cuphea* is influenced by fire. After a fire event, the number of flowers changes, and this causes the amount of nectar to change. Changes in the amount of nectar cause changes in the number of insects, and ultimately in the number of pollinated flowers.'

Note that there are two types of quantities in each statement, those that are the starting point for changes, and those that simply propagate changes. These roles are not necessarily played by the same quantity. For example, in (s.4.9), amount of nectar is the starting point, and the others propagate changes. In (s.4.10 and s.4.11), changes start in the number of flowers, and propagate to the rest. This observation matches with the two types of quantities identified in section 4.1.2.

These statements show the overlapping between how the quantities affect each other, and how their values are calculated. Actual calculations require the satisfaction of constraints that are better described in another layer: the mathematical structure.

c) The *mathematical structure* of the system specifies the mathematical constraints between the quantities. It is therefore a description of the operations involved in calculating the quantity values. For example, the equation (3) in section 4.1 describes the mathematical structure of the population. It says that, in order to obtain the value of N_{t+1}, B and I should be added to N_t, and then D and E should be subtracted from the total.

Considering that each state is characterised by specific values for the quantities, operations for calculating values are the key for simulating the system's behaviour.

Therefore the mathematical structure and the causal structure are, jointly or separately, sufficient requirements for building simulation models.

The mathematical structure may be used to support some types of explanation. For example, an explanation such as (4.12) is built upon the mathematical structure:

> (s.4.12) 'The number of non-pollinated flowers is large because the total number of flowers is large, the number of pollinated flowers is very small, and [large] = [large] – [very small].'

Obviously, this statement makes much more sense if there is knowledge linking these qualitative values to objects, and saying why the values should be added to produce the value of another quantity. These elements are represented in the conceptual structure of the system.

In conclusion, in the proposed framework, the physical structure of the system is decomposed into a conceptual structure, a causal structure and a mathematical structure. These three components encode different types of knowledge, and have different functions in the model. The conceptual structure encodes knowledge about objects, situations and mechanisms of change, and is essential for explanations, whereas the mathematical structure encodes procedures for value calculation and is essential for simulations. The causal structure encodes knowledge about primary and secondary causes of change, and provides support for both explanations and simulations.

Models hardly have these three components explicitly represented. Depending on the purposes of the model, one or two of them may remain implicit. Some examples can illustrate what type of knowledge is explicit and how it can be used:

1. Mathematical models (e.g. models based on differential equations) have the mathematical structure explicitly represented, but both the causal and the conceptual structures are left implicit. The framework explains why mathematical models are good

for simulations but not for explanations. These models are actually detailed representations of the mathematical structure. However, they lack representations of the causal relations and the concepts involved in the system, and thus can hardly be used to support explanations.

2. Influence diagrams are explicit representations of the causal structure of the system. In these models both the conceptual and the mathematical structures are implicit. Influence diagrams can be used for supporting simulations, but detailed calculations of the values of the quantities cannot be done. They also support explanations, but these explanations are just descriptions of the chain of influences, and do not refer to objects or to conditions for things to happen.

3. Finally, keys for the taxonomy of plants and animals based on morphological characteristics are models of these organisms described in terms of concepts. They have neither causal nor mathematical structures explicitly represented. These models can be used to support explanations, but are useless for simulations.

The three components (conceptual, causal and mathematical) used to describe the physical structure of the system do not have crisp limits, and may not have special meaning in themselves. However the framework proposed here offers a convenient way for describing and comparing models, as well as discussing the modelling process. The details of this framework are discussed in the following sections.

4.2.2 What is in the system?

In the qualitative models developed here, the system consists of objects. A system is any collection of interrelated objects. For example, an individual tree, a population of trees, and a community of cerrado can be seen as objects. It follows from the domain theory developed in section 4.1 that

> (s.4.13) 'In the studies described here, <u>population</u> is the most important object.'

Objects are domain knowledge organisers *par excellence* for building learning environments. The didactic discourse can be built around the objects, exploring some of their properties and situations in which they can be found in the world, and how they change over time. For example, size and mobility are examples of population's properties. Relevant properties are represented as quantities, each associated with a set of qualitative values (see section 4.2.3).

There are two different classes of relations between objects in the system:

a) Objects can be instances of more generic objects. For example, there is a generic object plant in the model, and the objects tree, shrub and grass. The relations between them can be described as

(s.4.14) 'tree, shrub and grass are types of plant.'

They share some (generic) properties, because they are plant. However, there is room for introducing specific properties they may have in the model. For example, being made of 'woody material' is a property of tree and shrub, but not of grass. The possibility of using similarities and differences between objects enhance the quality of the explanations generated in a learning environment.

b) Objects can be parts of other objects. For example, the objects

(s.4.15) 'flower, fruit, and leaf are parts of plant'.

In these cases, all the objects keep their own identities, although there is some sort of relationship between them represented in the model. From the perspective of explanation generation, this situation is useful for establishing relations between the whole and the parts of the objects. For example, from (s.4.15) we may say what the constituents of plant are.

Sometimes objects can be created or destroyed during the simulation. Introducing and removing objects causes changes in the physical structure of the system. For example, during the plant's life cycle flowers can appear and later change into fruits. Qualitative models should have enough flexibility for capturing and explaining these structural changes. They may involve changes in the conceptual, causal and mathematical structures, for example introducing concepts related to the objects flower and fruit, creating new causal relations, and defining new equations with new quantities.

Objects may have several properties. The relevant properties are represented in the models as quantities. For example,

> (s.4.16) 'The quantity number of trees represents a property of the object population of trees.'

Explanations require (a) an explicit link between the quantities and the objects they represent in the model, (b) the set of values each quantity can assume, and (c) some sort of semantics for understanding the relations between these values. In this example, there is a property of the object population of trees to be explored in simulations (its size), which is represented by number of trees. If the value for this quantity at a certain point is small, it is interesting to know whether there is any possible value smaller than small for that quantity. These points will be explored in the following sections.

4.2.3 How are the objects characterised?

It is not difficult to recognise fixed and changeable properties in the objects. These two types of properties can be associated with specific functions in the model. Fixed properties are useful for describing and classifying the objects. However, if they do not change, they have little interest for simulations representing the behaviour of the system. More interesting for this purpose are properties that can change under certain conditions.

For example, leaf is part of the object tree. The shape of the leaves and the number of leaves express different properties of tree. On the one hand, shape may be interesting for describing the tree species, but it is very unlikely that it affects the behaviour of the tree. On the other hand, the number of leaves may be interesting for describing the behaviour of these trees during the dry and the wet seasons. Given that the main concern of this thesis is modelling properties that may change (continuously) over time, a simulation model should include the number of leaves rather than their shape.

Continuous properties of the objects are represented in qualitative models as quantities. As discussed in section 4.1, quantities can be described on the basis of their magnitude, direction of change (derivative) or both (see statement s.4.1). If the system remains unchanged during a certain time interval, then only the magnitude is relevant. For example,

> (s.4.17) 'During the dry season, the number of leaves is small.'

In other situations, only the direction of change is relevant for describing the system's behaviour. For example, we do not need the magnitudes of the quantities to say:

> (s.4.18) 'The number of leaves is increasing in the beginning of the wet season.'

Finally, in some situations, quantities are better represented both by magnitude and derivative. This is often the case of the most important quantities for describing the system's behaviour (state variables). Statements (s.4.17) and (s.4.18) can be combined for saying

> (s.4.19) 'Given that the number of leaves is small and increasing, it will be large in the next time step.'

Obviously, numbers can assume infinite different values, although in general only few are really meaningful for the understanding of the system's behaviour. In qualitative modelling,

> (s.4.20) 'Each quantity must be associated with a set of values that describe qualitatively interesting phenomena.'

The criteria for selecting which qualitative values should be included in the model depends on both the domain knowledge and the purposes of the model. For example,

> (s.4.21) 'Possible values for the number of leaves may be <u>small</u> and <u>large</u>.'

It may happen that different representations for the same values are required in different contexts. For example,

> (s.4.22) 'The <u>large</u> number of leaves is <u>above the normal</u> expected for this time of the year.'

Here, the value <u>large</u> is compared with a different set of possible values that probably includes also the values <u>normal</u> and <u>below normal</u>.

Qualitative values can be either points or intervals. The former indicates a specific value associated with some relevant event on the system's behaviour. For example, the point <u>zero</u> is ubiquitously associated with quantities for representing the absence of things. Intervals indicate sets of point values associated with the same behaviour of the system. For example, the interval <u>small</u> can be associated with quantities that represent size, and might indicate a particular problem with the system.

In conclusion, objects are characterised by some of their properties. These are represented as quantities associated with a set of possible qualitative values. Building qualitative models requires a description of how quantities are related to each other. This point will be discussed in the next section.

4.2.4 How are the objects related?

The relationships among the objects in a system constitute a significant part of the domain knowledge. Given that objects are characterised by their properties, and properties are represented by quantities, in qualitative models relations between objects can be represented as relations between quantities. In general, relations between quantities describe the conditions for things to happen. For example, pollination requires the number of flowers greater than zero. Since the values of the quantities may change over the simulation, so the set of things that can happen with the system may also change at each state. For instance, if the number of flowers goes to zero during the simulation, then pollination no longer occurs.

Four types of relationship[11] between quantities are considered here: (a) inequalities; (b) causal relations; (c) functional relations; (d) constraints. They can be described as follows:

a) *Inequalities* represent some sort of comparison between the magnitudes of quantities. Comparisons of this type are often used in common-sense reasoning about objects. They include in the explanatory discourse notions such as greater than, smaller than, equal to, etc. For example,

> (s.4.23) 'The number of flowers during the dry season is <u>smaller</u> than the number of flowers during the wet season.'

b) *Causal relations* express how changes in certain quantities produce some effect in other quantities. They are very useful for supporting explanations because, as noted by Forbus (1984), there is a strong sense of direction in causal relations. For example,

[11] Bredeweg(1992) defines only two types of relations, Inequalities and Dependencies. However, a more detailed representation provides a wider vocabulary for explanation generation (see Chapter 7).

(s.4.24) 'Change in the number of pollinator insects causes change in the number of pollinated flowers.'

brings about the idea of something that comes from the pollinator insects to the pollinated flowers, not the contrary. Additionally, causality suggests temporal relationships between things. For example, one could infer from the previous example that

(s.4.25) 'Changes in the number of pollinated flowers occur after changes in the number of pollinator insects.'

c) More details about the causal relations may be provided by *functional relations*. They provide some indication of how the values of some quantities can be inferred from the values of other quantities. An example of this type of relation is

(s.4.26) 'When the number of pollinator insects is increasing, the number of pollinated flowers also increases.'

Sometimes our knowledge about the relation between two quantities is restricted to associations of certain values they have. For example,

(s.4.27) 'When the number of pollinator insects is zero, the number of pollinated flowers is also zero.'

d) Mathematical *constraints* are detailed specifications of how the value of a quantity can be calculated from the values of other quantities. For example,

(s.4.28) 'The total number of flowers is the number of non-pollinated flowers plus the number of pollinated flowers.'

Constraints may be applied to sets of quantities when it is fair to assume that all the values of the quantities required for the calculations are known (see the comments about equation 4 in section 4.1.3). If less information is available (for example, about the type of constraint relating two quantities), then functional relations can be used for calculating the values of quantities.

In the framework defined in section 4.2.1, both functional relations and mathematical constraints can be used for representing the mathematical structure of the system, because they support value calculation. However, only functional relations can be used to describe the causal structure, because constraints have no explicit knowledge about the flow of causality. Constraints are useful to represent non-causal relations.

Relations between quantities are important elements for representing ecological systems in qualitative models. Inequalities play an important role in defining both the conditions for things to happen and the effects of changes in the system. Causal relations express how changes flow within the system. Functional relations give more details about how causal relations affect the values of the quantities. Constraints are used to determine the values of the quantities. How can the system be described during the simulations? In the next section what should be included in descriptions of typical situations is discussed.

4.2.5 What typical situations describe the system's behaviour?

Qualitative descriptions of behaviour often include typical situations in which objects, their properties, and the whole system may be involved. The explicit representation of these typical situations can be done in terms of objects, the conditions for the situation to hold, and what the implications for the system are. Such descriptions include therefore all the elements discussed in the previous sections.

For example, plants with flowers can be described in a situation called <u>flowered plant</u>. The objects <u>plant</u>, <u>flower</u>, <u>soil</u> , and <u>cerrado</u> are involved in this situation. The size of the population, the quantity of flowers, the amount of water in the soil and the length of the day are the relevant properties of the objects. These properties can be represented by the quantities number of plant, number of flower, soil water and daylength.

The conditions for a situation to hold are often defined by specific inequalities between the quantities. For instance, flowered plant exists when plants and flowers are both greater than zero, and soil water and daylength are both greater than a given minimum value.

When the objects are in a particular situation, some effects on the system may be observed. For example, flowered plant may introduce the object nectar and the quantity amount of nectar in the system. The amount of nectar is influenced by the number of flowers. The existence of nectar in turn may create the conditions for other things (such as pollination) to occur.

These elements altogether may be used for saying

> (s.4.29) 'Plants are flowered when the number of flowers is greater than zero, and both the amount of soil water and the day length are above certain limits. Flowered plants produce nectar, and the amount of nectar is influenced by the number of flowers.'

Situations describe static aspects of the world. However, the system changes over time. For instance, flowered plant is the result of an important physiological mechanism (flowering), that causes flowers to appear in non-flowered plants. The description of these mechanisms of change is discussed in the next section.

4.2.6 What can cause change in the system?

As far as objects and their properties are concerned, everything can change. Qualitative models designed to support simulations and explanations must have a clear representation of the physical, biological or ecological mechanisms that cause changes in the system.

There are many different mechanisms producing changes in ecological systems. These mechanisms may be complex and very different when compared among themselves. However, it is possible to abstract some common aspects in representing them in qualitative models. As in describing situations (section 4.2.5), descriptions of mechanisms of change include the objects and the quantities involved, the conditions for these mechanisms to become active, and the effects they produce in the system.

For example, reproduction in flowered plants starts with a mechanism called pollination. It may be mediated by some pollinator insect, attracted by the nectar produced in the flowers. As a consequence, non-pollinated flowers become pollinated flowers. This mechanism of change, pollination, can be described as follows. The objects involved are plant, non-pollinated flowers (flower) and insect. They are represented by the quantities number of plant, number of flower and number of insect.

The conditions for mechanisms of change (and for situations) to become active are often described by inequalities. For example, pollination requires the number of insect to be greater than zero. Sometimes specific situations must hold for a mechanism of change to become active. For example, for pollination to occur it is necessary that flowered plant already exists. In cases like that, there are implicit requirements for the mechanism of change to be active: both number of plant and number of flower must be greater than zero (see section 4.2.5).

In general, these mechanisms change some properties of the objects, and cause the value of quantities to change. They may also introduce new objects into the system. For example, pollination introduces a new type of object, pollinated flower, which replaces (non-pollinated) flower.

Mechanisms of change affect directly some quantities, and may propagate their effects to other objects and quantities (see sections 4.1 and 4.2.3). The *direct* consequences of pollination, for example, are changes in the objects flower and pollinated flower. These effects determine the direction of change in the quantities number of flower and number of pollinated flower. When pollination occurs, the former decreases, and the latter increases. The effects of pollination may propagate to other components such as, for example, the production of seeds. We can say then pollination *indirectly* influences the number of seeds.

However, mechanisms of change require some sort of control that determines when the process should stop. In this case, a possible control is exerted by the quantity number of flower. It can be expressed as follows:

> (s.4.30) 'Non-pollinated flowers are required for pollination to occur. However, pollination causes the number of non-pollinated flowers to decrease. Therefore, pollination will stop when there are non-pollinated flowers left.'

The elements discussed in this section support the following utterance:

> (s.4.31) 'Pollination is a mechanism that transforms non-pollinated flowers into pollinated flowers. It requires the presence of flowered plants and pollinator insects. Pollination makes the number of non-pollinated flowers decrease, and the number of pollinated flowers increase. Indirectly, it may affect the number of seeds.'

Situations (section 4.2.5) and mechanisms of change describe important concepts about the system. How to combine these elements for producing more complex representations of ecological systems is discussed in the next section.

4.2.7 Building more complex representations of the system

A quite common approach for handling complex systems in any modelling formalism is to represent smaller and simpler components, and then combine these partial models to obtain a more complex description of the system. Representations of situations and mechanisms of change (sections 4.2.5 and 4.2.6) are examples of this approach. The expectation is that

> (s.4.32) 'If there is a set of independent partial models of situations and mechanisms of change, then they can be combined to create different representations of the system, with different levels of complexity.'

It is important to keep these partial pieces of knowledge as independent as possible, so they can be assembled in different ways. This property of qualitative modelling is called *compositionality*, and is an important issue for QR (see, Falkenhainer & Forbus (1991) and Addanki *et al.* (1989), for two different approaches to this problem, and Schut & Bredeweg (1996) for an overview of the related problems).

Partial models must have a clear distinction between knowledge that is condition for them to be selected, and knowledge about the consequences of having these partial models included in the description of the system. This point has both epistemological and practical reasons. First, a relevant part of the explanatory discourse refers to the conditions for situations and mechanisms of change to be active. Once these conditions are met, it might be easier to understand the implications they have for the system's behaviour. From the practical point of view, the separation between conditions and givens makes it easier for the qualitative inference engine to derive when one particular partial model applies, and the new knowledge that can be added to the behaviour description (see Bredeweg (1992), for an account of the types of knowledge involved in the conditions and givens of partial models).

For example, pollination may be defined in a partial model as follows:

(s.4.33)

'IF

there are plants

and plant has quantity number of plants

and plant has part flower

and flower has quantity number of flowers

and there are insects

and insect has quantity number of insects

and environmental conditions are favourable

and number of plants is greater than zero

and number of flowers is greater than zero

and number of insects is greater than zero

THEN

there is pollination

and there are pollinated flowers

and pollinated flower has quantity number of pollinated flowers

and pollination changes according to the number of flowers

and pollination changes according to the number of insects

and pollination causes number of flowers to decrease

and pollination causes number of pollinated flowers to increase'

Given that these partial descriptions can be assembled to compose a model of the system under specific conditions, it may happen that different assemblies are created during the simulation. It is therefore possible to represent changes in the physical structure of the system, in which objects (and quantities) are included and removed.

For example, there is a period of time during a plant's life cycle when there are no flowers. Depending on the conditions, next comes a period in which flowers are produced. Finally the flowers may be replaced by fruits. The life cycle of this plant may be described by situations such as <u>non-flowered plant</u>, <u>flowered plant</u>, <u>pollinated plant</u>, <u>plant with fruit</u>, and mechanisms of change such as <u>flower production</u>, pollination, fruit production. The 'givens' introduced by each partial model satisfy the 'conditions' for the other partial models. Then the system's behaviour can be simulated by combining situations and mechanisms of change as follows:

{ non-flowered plant , flower production } ==> { flowered plant , pollination } ==>

==> { pollinated plant , fruit production } ==> { plant with fruit }

where each state is represented with the set of partial models between brackets[12]. These changes in the system may be described in terms of the conceptual, the causal and the conceptual structures proposed in section 4.2.1.

The requirements for building qualitative models about the dynamics of the vegetation were discussed in sections 4.1 and 4.2. In the next section, the languages used to implement these ideas in qualitative models are presented.

4.3 The modelling languages

As discussed in Chapter 2, QPT and SIMAO are the modelling languages selected to implement the models described in this thesis. Recall that QPT has the modelling primitives for representing the conceptual and the causal structures of the system, but the mathematical structure cannot be expressed in detail with this language, whereas SIMAO has a well developed qualitative algebra that allows for the representation of the mathematical structure, but is not adequate for explicitly representing concepts and the causal relations. It will be shown in this section that, combined, these two formalisms provide a powerful set of modelling primitives for building qualitative models that can be used in learning environments for support simulations and explanations.

[12]Some of these views and mechanisms of change will be discussed in section 4.3.5.

4.3.1 Objects

In QPT-based models, objects are used to organise the library of model fragments. This can be achieved with structured representations of the objects. For example, using *isa* and *partof* hierarchies, it is possible to express relations between objects such as those expressed in the statements (s.4.14) and (s.4.15)[13]:

English statement	Formal representation
(s.4.14)	isa(plant, biological_entity) isa(tree, plant)
(s.4.15)	has_attribute(plant, has_part, flower)

From the formalizations above, it can easily be derived that trees have flowers. To support explanations additional knowledge can be used providing better descriptions of attributes of the objects. For example, it may be interesting to know that flower has colour white. Similar representations could be applied to shrubs, grass, fruits and leaves.

Some characteristics of an object might be relevant for simulations. These characteristics are represented as *quantities*. Quantities are associated with the objects they belong to, a requirement mentioned in statement (s.4.16). This can be formalized as follows:

English statement	Formal representation
(s.4.16)	has_quantity(tree, number_of (tree))

Details of the representation of quantities are presented in the next section.

[13]The English statements presented in sections 4.1 and 4.2 will be compared to their representational equivalents throughout this section.

4.3.2 Quantities and Quantity Spaces

It is convenient for calculations that objects are modelled as a bundle of quantities. Their qualitative values are represented as numbers[14] that have two parts: *amounts* and *derivatives*. The amount refers to the common-sense notion of how big the number is. The derivative is a notion required in dynamic models to indicate how the quantity is changing. Both amount and derivative are also numbers with *magnitude* and *sign*. Therefore a complete representation of the value of a quantity is a tuple with the following elements:

Value_of_Quantity = < Amount_of_Quantity, Derivative_of_Quantity >

represented in this thesis[15] as [Q] = < A[Q], D[Q] >

Amount and Derivative each have magnitude and sign:

Amount_of_Quantity = < Magnitude_of_Amount, Sign_of_Amount >
Derivative_of_Quantity = < Magnitude_of_ Derivative, Sign_of_ Derivative >

or [Q] = < (Am[Q], As[Q]) , (Dm[Q], Ds[Q]) >

However, only some of the elements in the definition of a quantity are relevant for the purposes of the models described in this thesis. Firstly, in ecological systems, amounts of quantities seldom have negative sign (As[Q] = –). Therefore, it is assumed in this thesis that the amount of the quantity is represented by its magnitude, < Am[Q] > with a positive sign.

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[14] It is important to notice that, although the word 'number' is being used, numerical values are not included in any model described in this thesis.
[15] The notation for quantities and other modelling primitives, such as proportionalities and influences, is the same as that used by Forbus (1984).

Secondly, derivatives carry information about the direction of change (Ds[Q]) of the quantity. This can be translated as 'increase' and 'decrease'. Derivatives also express the notion of how fast the change is happening, through the component < Dm[Q] >. Some models described in this thesis are based only on QPT. In these cases, derivatives are expressed by their sign. The value zero for the magnitude of the derivative is used to represent no changes in the quantity. Models using the SIMAO qualitative algebra (Chapter 5) may represent the actual calculations of the values of < Dm[Q] >.

The formal representation of these elements meets the requirements presented in different statements, such as (s.4.1), (s.4.17) and (s.4.18):

English statement	Formal representation
(s.4.1)	[Q] = < A[Q], D[Q] >
(s.4.17)	[Q] = < A[Q] >
(s.4.18)	[Q] = < D[Q] >

A crucial problem for qualitative reasoning is the quantification of the properties of the objects: how to map the different values quantities can take in the real world to a representation as a meaningful set of symbols in qualitative models. In principle, continuous properties can assume infinite numerical values. Reasoning qualitatively about quantities requires some abstractions with respect to possible values they can assume. This requirement was expressed in the statement (s.4.20). The set of symbols used to represent values of quantities is by definition limited, and thus qualitative models should include only those values that correspond to relevant distinctions in the system's behaviour. Forbus (1984) calls this the *relevance principle.*

Possible values a quantity can assume in qualitative models are described in a set called the Quantity Space (QS). For example, statement (s.4.21) can be formalized as follows:

English statement	Formal representation
(s.4.21)	QS = { small, large }

QS can include points, intervals or both. Signs are a very intuitive and powerful representation of qualitative values. For example, derivatives can take on the values { –, 0, + }, two intervals and one point, to represent respectively 'decreasing', 'steady' and 'increasing'.

Some points in the QS can be called *limit points* (Forbus, 1984). They have special interest because these are values where discontinuous changes in the system occur. For example, points where processes either start or stop. Limit points serve as boundary conditions and are chosen according to the processes which affect that quantity.

For instance, modelling the behaviour of a population with a known carrying capacity (K)[16], a simple QS for the number of plants such as

{zero, below_K, K, above_K}

suffices to model the most important population phenomena. Both zero and K are limit points because relevant phenomena occur when these values are reached: the population disappears (zero) or stabilises (K).

In many cases, however, the QS consists only of intervals. For example, SIMAO's qualitative algebra, largely used in the models described in Chapter 5, is based on a scale of five intervals. A typical example of such a QS is

{ very_small, small, medium, large, very_large }

Forbus (1984) points out that the elements of a particular QS are determined by the comparisons needed to establish certain kinds of facts, such as whether or not processes are acting. Consequently, different QS's can be used for the same quantity, according to the purposes of the model or the context of the simulation. For example,

[16] Carrying capacity is the number of individuals that corresponds to the maximum density that can be sustained in a certain environment.

a QS can be used to describe the behaviour of a quantity in specific situations, and a different QS can be used to express its behaviour at any time. The temperature of the water in a lake could be represented as follows: QS = {plus} during the summer time, and QS = {minus, zero, plus} during the whole year.

Reasoning with more than one quantity at the same time, or reasoning with different values of the same quantity at different times or locations, requires more elaborate representations of qualitative values. In general, it is necessary to establish some sort of correspondence between the values in the QS's. The correspondence can be one value to one value, or one value to many values, depending on the number of possible values and their meaning. For example, the QS's for number of trees and the amount of shade can be related one to one as follows:

QStrees = {zero, few, medium, many} and QScover = {zero, small, medium, large}

Situations involving the notions of *absolute qualitative value* and *relative qualitative value* may require correspondences of type one to many. For example, a quantity can have a certain (absolute) value established according to some scale using the QS = {very_small - very_large} shown above. This absolute value can have a functional interpretation within the system, which is its relative value. These relative values can be expressed with the QS = {below_normal, normal, above_normal}.

It may be the case that the (absolute) values {very_small, small} correspond to the (relative) value {below_normal} (see statement s.4.22). Absolute and relative values are recurrent expressions in the analysis of dynamic systems. The relation between different QS can be implemented using a QPT primitive called *correspondence*. This primitive will be explained in more detail in the next section (section 4.3.3).

An important point to note here is that values in the QS cannot be skipped during the simulation. This is a well established rule in qualitative modelling, called *the continuity rule* (de Kleer & Brown, 1984). It states that each variable varies continuously. Therefore, all the changes in a quantity occur from one value to an adjacent value in the QS. This applies both to amounts and derivatives. For example, this is the formal justification for the statement (s.4.19), assuming that the number of leaves have QS = {small, large}.

Obviously, quantities are important components of both qualitative and quantitative simulation models. In its original implementation (Guerrin 1991), only magnitudes were represented in SIMAO. This is not however a limitation of the modelling language itself. It will be shown in Chapter 5 that derivatives can also be included in SIMAO-based models. Mathematical models based on differential equations also have representations for magnitudes and derivatives. System Dynamics, for example, is a reference for the qualitative models described in Chapter 5.

Values in the QS represent the behaviour of a quantity. In this sense, it should be possible to have a good preview of what can happen to a quantity by inspecting its QS. The QS includes all the possible behaviours that quantity can show (in a particular context). By extension, possible behaviours a system can display could be roughly inferred by inspecting the QS of the quantities. This relation between value and behaviour provides a useful vocabulary to support explanations, as discussed in Chapter 7.

4.3.3 Relations between quantities

As discussed in section 4.2.4, it is possible to recognise four types of relations between quantities: inequalities, causal dependencies, functional relations and constraints. Inequalities can be implemented in any of the modelling languages, QPT and SIMAO. QPT's modelling primitives (influences and qualitative proportionalities) have causal and functional interpretations, and may give some indications of the sort of constraints between the quantities that can be applied to a particular situation. SIMAO in turn does not provide primitives to represent causal and functional relations, but allows for the representation of constraints. In this section it is shown how QPT can be combined with SIMAO for implementing qualitative models. Each type of relation is discussed below.

Inequalities have a straightforward interpretation, and can be easily implemented. For example, in the statement (s.4.23), the number of flowers during the dry season (Q1) is compared with the number of flowers during the wet season (Q2). This can be represented as follows:

English statement	Formal representation
(s.4.23)	Q1 < Q2

Causal relations and functional relationships are very important for implementing the core ideas of QPT. As mentioned in section 4.3.2, QPT defines two kinds of influences on quantities: *direct influences*, which can only be caused by processes, and *indirect influences*, which propagate changes caused by processes. Direct influences are modelled as *influences*, and indirect influences are modelled as *qualitative proportionalities*.

For example, in the statement (s.4.31) the number of pollinated flowers (Q1) is directly influenced by the pollination (represented by Q2, the quantity pollination_rate), and it is an indirect influence on the number of seeds (Q3). This can be formalized as follows:

English statement	Formal representation
(s.4.31)	I + (Q1, Q2) Q3 α_{Q+} Q1

Both direct influences and proportionalities have a causal interpretation and a functional interpretation. According to the framework outlined in section 4.2.1, these modelling primitives are appropriate for representing the causal structure, and may be useful for implementing the mathematical structure of the system (see Forbus & de Kleer, 1993).

Dynamics is expressed by the notion of direct influence. For example, consider the following direct influence:

$$I+(Q1, Am[Q2])$$

where Q1 is the directly influenced quantity, and Q2 is the rate of the process. The causal interpretation of this expression is 'Q2 causes change in Q1', never the contrary. This expression has also a mathematical interpretation. It means that the amount of Q2 (represented by Am[Q2]) is used for calculating the derivative of Q1, that is, D[Q1]. However the final value of the D[Q1] is not fully defined yet: in a direct influence there's no information about the possible existence of other direct influences. In QPT, the operation of combining influences (both direct and indirect) is called *Influence Resolution*.

If Q2 is the only direct influence acting on Q1, it is easy to do the influence resolution: the derivative of Q1 takes the value of the amount of Q2:

$$D[Q1] = Am[Q2]$$

For example, suppose that the process *Pollination* introduces only one direct influence on the number of pollinated flowers (see statement s.4.31):

I+ (number_of(*Pollinated_Flowers*), Am[*pollination_rate*])

This can be read as follows: <u>pollination rate</u> has a positive direct influence on the number of pollinated flowers; assuming that this is the only active direct influence, the derivative of number of pollinated flowers takes the value of the rate:

D[number_of(*Pollinated_Flowers*)] = Am[*pollination_rate*]

As the influence is positive (I+) and the rate is also positive ($Am[Q2] > 0$), the number of pollinated flowers will increase by an amount equal to <u>pollination rate</u>. If the number of flowers that are pollinated within a certain time interval had been measured, it could be used as the value of pollination rate. This is the approach taken in the models combining QPT and SIMAO presented in Chapter 5.

In other models (Chapter 6), the values of the rates (the amount of the derivative) are not calculated, and only their sign are used. In the example above it corresponds to saying that the sign of the derivative is positive (because the value of pollination rate is greater than zero), and thus the number of pollinated flowers is increasing.

A similar representation can be used to express the influence of *Pollination* on the number of non-pollinated flowers:

I– (number_of(*Non-pollinated_Flowers*), Am[*pollination_rate*])

Since the influence is negative (I–) and the rate is positive, then the number of non-pollinated flowers will decrease by an amount equivalent to the amount of the rate. From these two examples, it is easy to derive the interpretations for the influences of rates with negative values:

a) if the rate is negative, a positive influence sets a negative derivative and causes the quantity to decrease;

b) if the rate is negative, a negative influence sets a positive derivative and causes the quantity to increase.

If there is more than one direct influence acting on a particular quantity, then the effects of all influencing quantities must be combined *by addition*. When the influences have the same sign, the result can easily be calculated:

if I+ (Q1, Q2)

and I+ (Q1, Q3)

then D[Q1] = Q2 + Q3

However, if the direct influences have opposite sign, the result is ambiguous. For example,

if $\quad Q2 > 0$

and $\quad Q3 < 0$

then $\quad D[Q1] = Q2 + Q3 = ?$

To solve this ambiguity additional information is required. If it is known which influence is greater (for instance, $Q3 > Q2$), then the final result ($D[Q1]$) takes the sign of that influence (negative). However, if the ambiguity cannot be solved, an option to carry on with the simulation is to try all the possibilities concerning the magnitude of the direct influences. The result of all these operations is branching in the envisionment graph.

After computing the effects of processes and assigning new values for the directly influenced quantities, changes can be sent out to the other quantities. These other quantities are said to be *indirectly influenced*, because they are not affected directly by processes in the current model, but their values change because of the effects of some process. These indirect influences are modelled by *qualitative proportionalities* (α_Q).

Proportionalities describe how a certain quantity will change depending on changes in another quantity, all else being equal. They also have a causal and a mathematical interpretation. Given the expression

$$Q1 \; \alpha_Q \; Q2$$

the causal interpretation is that Q2 causes Q1 to change (and never the contrary). A qualitative proportionality clearly states which quantity is the causal agent and which is being influenced. They can also be combined to represent chains of causal influences. Therefore, it can be used as a solution for the representational problem posed by statements such as (s.4.9), (s.4.10), and (s.4.24):

English statement	Formal representation
(s.4.24)	Q1 α_Q Q2
(s.4.9)	Q1 α_Q Q2 Q2 α_Q Q3
(s.4.10)	Q1 α_Q Q2 Q2 α_Q Q3 Q3 α_Q Q4

The mathematical meaning of α_Q is that there exists some monotonic function that could be used (if it is known) for determining the change of one quantity on the basis of how another quantity changes, all else being equal. The effect of this relationship is that the derivative of Q1 takes the value of the derivative of Q2.

If the function is strictly decreasing, then it is represented as α_{Q-}, and if it is strictly increasing, as α_{Q+}. For example, the interpretation of an expression such as Q1 α_{Q+} Q2 is that when Q2 changes, it causes Q1 to change as well, in the same direction. Thus, when Q2 is increasing, and it is the only influence on Q1, then Q1 also increases. Similarly, Q1 α_{Q-} Q2 means that when Q2 changes, it causes Q1 to change in the opposite direction: for example, if Q2 is increasing, then Q1 decreases. The statement (s.4.26) can be formalized as follows:

English statement	Formal representation
(s.4.26)	number_of(*Pollinated_Flowers*) α_{Q+} number_of(*Insects*)

It is important to notice that the proportionality carries little information in itself: it neither specifies *what* the relation between those two quantities is, nor whether there are other quantities affecting the influenced quantity (which is the meaning of *all else being equal* in the definition above). For instance, in the expression Q1 α_{Q+} Q2, the correspondent mathematical function relating Q1 and Q2 could be addition, multiplication, a trigonometric function or a polynomial function. Moreover, the final value of the derivative of Q1 cannot be determined exclusively from this expression, unless we know that this is the only active influence on Q1. In this case, the derivative of Q1 will take the same value as the derivative of Q2.

Another QPT primitive, the *correspondence*, can be used to represent more information about the function which has been modelled using proportionalities. As mentioned in the previous section (4.3.2), this primitive is used to establish the correspondence between values assumed by different quantities, possibly using different QS's. They can also be used to express correspondence of the whole QS's of the two quantities (Bredeweg, 1992). Formally correspondences may be represented as

$$Q1 \quad \alpha_Q \qquad Q2$$

correspondence((Q1, v1) , (Q2, v2))

and can be read as 'when quantity Q2 assumes value v2, then quantity Q1 takes on value v1'. For example, given the proportionality relating pollinated flowers and pollinator insects above (and the statement s.4.26), we can add information to the model saying, as in the statement (s.4.27), that when there are no pollinator insects, there are no pollinated flowers. This can be done by using a correspondence:

English statement	**Formal representation**
(s.4.27)	correspondence((number_of(*Pollinated_Flowers*), zero) , (number_of(*Insects*), *zero*))

In some situations, it may be interesting to calculate the magnitudes of quantities, instead of just focusing on their derivatives. Qualitative proportionalities are the major building blocks for equations (Forbus & de Kleer, 1993). If more knowledge is available, specific expressions can be created for explicitly representing the constraints that are implicit in proportionalities.

This task requires some sort of qualitative algebra. As mentioned in Chapter 2, SIMAO (Guerrin 1991; 1992) can be used for complementing the mathematics of QPT. This point is discussed in the next section.

4.3.4 Representing the constraints between quantities qualitatively

As discussed in the previous section, QPT has modelling primitives (direct influences and proportionalities) that can represent the causal structure of the model. However, they are weak indications of the mathematical functions that actually represent the mathematical structure of the system. This is where SIMAO comes in: it provides a qualitative algebra that allows for the representation of constraints in qualitative equations and calculation of the values of the quantities.

SIMAO's qualitative algebra was developed empirically in an ecological context, and is described in Guerrin (1991; 1992). The Quantity Space typically assigned for the quantities in SIMAO-based models consists of five intervals represented by the symbols {pp, p, m, f, ff}. They may correspond, for example, respectively, to the values {very_small, small, medium, large, very_large }. This QS is completely ordered. Therefore

$$pp < p < m < f < ff$$

The qualitative algebra is based on three unary operators and three internal laws for combining influences between quantities. The unary operators are <u>increase</u>, <u>decrease</u> and <u>inverse</u>. The three internal laws are <u>addition</u>, <u>subtraction</u> and <u>multiplication</u>. These laws have some minimal properties (commutative, associative, distributive) required for calculations. A summary of these operators and internal laws is presented[17] in the following Table (4.1):

[17] All the examples of operations shown in this table are based on tables for combining qualitative values presented in Guerrin (1991; 1992).

Operator / Law	Typical operation	Example
increase[18]	increases the qualitative value of a quantity (x) in one (n=1) or more steps (n=2, n=3, ...) in the QS	incr(pp,1) = p
decrease	decreases the qualitative value of a quantity (x) in one (n=1) or more steps (n=2, n=3, ...) in the QS	decr(p,1) = pp
inverse	gives the inverse value in the QS, centred around 'm'	inv(p) = f
addition	adds a qualitative value to another	p + f = f
subtraction	subtracts a qualitative value from another	f – p = f
multiplication	multiplies a qualitative value by another to get a third one	f * m = f

Table 4.1 Operators and internal laws in SIMAO's qualitative algebra.

SIMAO's qualitative algebra can be used to implement qualitative equations, such as the one presented in the statement (s.4.28), and to make calculations such as the one presented in the statement (s.4.12). If we represent the total number of flowers as TF, the number of non-pollinated flowers as NPF and the number of pollinated flowers as PF, and use the QS = {very_small - very_large } defined above, the formal representation of the two statements is the following:

English statement	Formal representation
(s.4.28)	TF = NPF + PF
(s.4.12)	NPF = TF – PF ==> f = f – pp

Tables with the qualitative calculus based on these six operators/laws are presented in (Guerrin, 1991).

This qualitative algebra provides a language for expressing the constraints between quantities that are only hinted at in proportionalities. The possible interpretations of QPT's proportionalities within the SIMAO's algebra are presented in Table 4.2:

Proportionalities	Operator / law
positive proportionality	increase, addition and multiplication
negative proportionality	decrease, inverse, and subtraction

Table 4.2 Possible algebraic interpretations for proportionalities.

[18]Both the operators <u>increase</u> and <u>decrease</u> cannot use n >= 2 for calculating the value of the same quantity in subsequent time steps, because it skips values in the QS and violates the *continuity rule* (see section 4.3.2).

For example, the following proportionalities

$$Q1 \ \alpha_{Q+} \ Q2$$

$$Q1 \ \alpha_{Q-} \ Q3$$

may be represented in more detail with SIMAO's algebra as the qualitative equation

$$Q1 = Q2 - Q3$$

Note however that a closed world assumption is required for this equation to be valid. Proportionalities represent the effects of one quantity on another, when there are no other active influences on the same quantity. The qualitative equation instead represents what we believe are all the constraints on a quantity.

4.3.5 Views

Individual Views (or just *Views*) are described in terms of the modelling constructs defined so far: objects, quantities, and quantity relations. These elements are combined for representing general knowledge about the system and its components. Accordingly, views can apply to different situations: they can be used both as input for simulations, and for describing the effects of changes in the system.

Views include information about the objects involved in that particular situation, the conditions for the situation to hold and the relationships between objects and quantities that become true when the view is active. A view has four parts: *Individuals*, *Preconditions*, *Quantity Conditions*, and *Relations*. The example presented in Figure 4.1 is the formal representation of the statement (s.4.29):

***Flowered Plant* view**

Individuals

Object Plant is a composite object.
Plant has part object Flower
Object Cerrado is a composite object
Cerrado has part object Soil

Plant has quantity number_of(*Plant*)
Flower has quantity number_of(*Flower*)
Cerrado has quantity Daylength
Soil has quantity SoilWater

Preconditions

environment favourable

Quantity Conditions

number_of(*Plant*) > zero
number_of(*Flower*) > zero
SoilWater > minimum value
Daylength > minimum value

Relations

There is an object Nectar
Nectar has quantity amount_of(*Nectar*)
amount_of(*Nectar*) α_{Q+} number_of(*Flower*)
number_of(*Flower*) α_{Q+} number_of(*Plant*)
number_of(*Flower*) α_{Q+} SoilWater

Figure 4.1 Individual View *Flowered Plant*.

Each part of a view can be described as follows:

- *Individuals* are lists of objects, such as plants and flowers, that are instantiated for describing particular situations. This part also includes the quantities of the objects to be considered in the reasoning process, and their quantity spaces[19].
- *Preconditions* are statements referring to the external conditions necessary for the view to be active. These conditions are not affected by processes, and their values often cannot be deduced by inferences supported by QPT. In this example, these conditions are represented by a generic statement about the environment.
- *Quantity Conditions* are either statements about inequalities between quantities of the view's objects, or indications of other views and/or processes that must be already active. Unlike those declared in the Preconditions, restrictions stated here can be affected by processes. For example, plants and flowers must exist for the

[19]Quantity Spaces are omitted in order to simplify the descriptions of both views and processes.

view *Flowered Plant* to be active. If, for example, mortality eliminates all the plants, the view cannot be active.

- *Relations* contain statements about the relationships between quantities that hold when the view is active. Consequences from the view being active include new quantities being created, and indirect influences being transmitted between quantities. For example, when *Flowered Plant* is active, it creates an object[20] (nectar) and a quantity (amount of nectar). The amount of nectar is indirectly influenced by the number of flowers, which is in turn influenced by number of plants and soil water.

4.3.6 Processes

In QPT, *processes* are the only mechanisms that can cause change in the properties of objects. This is a cornerstone of QPT, expressed in the *sole mechanism* assumption (Forbus, 1984). They represent the formalization for the requirements expressed in section 4.2.6 (statement s.4.31) and section 4.2.7 (statement 4.2.28). Descriptions of processes include knowledge about objects and quantities, conditions for the process to be active, and relationships between quantities that are true when the process is active. The formalizatiốn of processes includes the same modelling constructs used for describing views: *Individuals*, *Preconditions*, *Quantity Conditions*, and *Relations*. However, only processes have a fifth part, *Influences*. This is used to represent primary causes of change, that is, the direct influences. An example, process *Pollination*, is presented in Figure 4.2. It is a formalised representation of the statement (s.4.33).

[20]This is an example of the mixture of knowledge discussed in section 2.3.2: an 'individual' (nectar) is being represented as a relation.

Process *Pollination*

Individuals

Object Plant is a composite object
Plant has part object Flower
Insect is an object
Plant has quantity number_of(*Plant*)
Flower has quantity number_of(*Flower*)
Insect has quantity number_of(*Insect*)

Preconditions

environment favourable

Quantity Conditions

Active *Flowered plant* view
number_of(*Insect*) > zero

Relations

There is an object Pollinated Flower
Pollinated Flower is part of object Plant
Pollinated Flower has quantity number_of(*Pollinated_Flower*)

Plant has a quantity pollination_rate
pollination_rate α_{Q+} number_of(*Flower*)
pollination_rate α_{Q+} number_of(*Insect*)

Influences

I+ (number_of(*Pollinated_Flower*), Am[*pollination_rate*])
I– (number_of(*Flower*), Am[*pollination_rate*])

Figure 4.2 Process *Pollination*.

The first four parts can be read as a view (see the previous section). In the slot *Influences*, the effects of the process are described: some quantities are directly influenced by a quantity (a rate) introduced by the process. For example, *Pollination* has two effects: it increases the number of pollinated flowers and reduces the number of non-pollinated flowers (because the latter are transformed into the former).

It is interesting to note the representation of a feedback mechanism in *Pollination*. The number of (non-pollinated) flowers exerts some control in the process, because it is a causal influence on the rate of pollination. The feedback is implemented as a two step process. When the number of non-pollinated flowers decreases, it makes the rate of pollination also decrease. This relationship expresses a secondary effect of the process, and the quantity pollination rate is indirectly influenced by the process. In the next step, the decreasing pollination rate influences number of non-pollinated flowers. The requirement expressed in the statement (s.4.30) can therefore be formalised as follows:

English statement	Formal representation
(s.4.30)	I – (Q1, Q2) Q2 α_{Q+} Q1

Mechanisms of (negative) feedback are often associated with the equilibrium of ecological systems. Negative feedbacks are represented by the combination of direct and indirect influences with *opposite* signs. In the example above, { I– and α_{Q+} }. The other possibility is { I+ and α_{Q-} }. In fact, in QPT-based models feedbacks always include a directly influenced quantity. As pointed out by Forbus & de Kleer (1993), directly influenced quantities 'ground' changes in the action of physical processes, thus breaking the feedback loops and allowing for a consistent account of causal relationships between the quantities.

4.3.7 Structured representations of views and processes

As discussed in the previous two sections, views and processes describe situations and mechanisms of change, which are comprehensive concepts. Structured representations of views and processes with *isa* and *partof* hierarchies provide even better representations of the domain knowledge.

For example, *Kielmeyera coriacea* is a common species of tree in cerrado areas. It is possible to define the object <u>kielmeyera</u> as a kind of <u>plant</u>. This way, a model fragment (*Flowered Kielmeyera view*) could be defined as an instance of *Flowered plant view*, and relationships defined in the latter (e.g. the influence of soil water on the number of flowers) are applicable also to <u>kielmeyera</u>.

The *partof* hierarchy in turn may be used for representing a complex view that can be decomposed into less complex ones. For example, the definition of the parts of a plant can follow this approach. After having defined a *Tree view*, it could be decomposed in *Root view*, *Trunk view*, *Leave view*, *Flower view*, *Fruit view* and *Seed view*. Therefore, it would be possible to express things such as 'the <u>root</u> of <u>kielmeyera</u>'.

Processes can also be represented in a structured way. The *isa* hierarchy can be used for defining instances of more general processes. For example, *Germination* and *Resprouting* (asexual production of new individuals) can be seen as special types of the *Natality* process. Similarly, complex processes can be decomposed into less complex processes. For example, the process *Succession* can be understood as a combination of processes occurring in the different populations of the community.

It follows from this discussion that, in qualitative models, processes can be lumped together (*aggregation*) or expanded (*disaggregation)*, according to the purposes of the model and the convenience of the modeller. Aggregation and disaggregation of processes can be associated with ecological phenomena on different scales (see Salles & Bredeweg, 1997). For example, the growth of populations of different species (population level) can be aggregated in processes such as *Succession* (at a higher organisational level, the communities). Process *Population growth* (at the level of populations) in turn can be disaggregated in processes such as *Natality*, *Mortality*, *Emigration* and *Immigration* (at the level of individuals). This point will be further developed in Chapters 5 and 6.

In conclusion, views and processes may include most of the elements necessary for representing the conceptual, the causal and the mathematical structures of ecological systems (according to the requirements presented in sections 4.1 and 4.2). They therefore provide the vocabulary necessary for describing the behaviour of the system. This point is discussed in the next section.

4.4 Describing the behaviour of the system

Behaviour can be seen as a sequence of states the system goes through, during a simulation. Several bits of knowledge may be required to describe each state of the system. Different bits of knowledge may be required to describe different states. Considering that a domain theory (section 4.1) is implemented as a library of model fragments (views and processes), this means that different subsets of the library may be involved in the representation of different states. This is the implementation of the requirement presented in statement (s.4.32). This section is concerned with the selection of active model fragments and calculation of the values of the quantities during a simulation.

4.4.1 Defining the view and the process structures

In simulations with QPT-based models each state of the system is described by the *view structure* and by the *process structure* (Forbus, 1984). They are, respectively, all the views and processes instantiated (active) during the time interval that corresponds to a state.

The instantiation of views and processes depends on the current description of the system. If the situation of the objects and the values of their quantities satisfy the set of conditions specified in each model fragment (see sections 4.3.5 and 4.3.6), then it becomes active. The model fragment is then included in the current description of the system, and the knowledge represented in its givens holds. Information about the conditions for views and processes to apply are presented in the slots *Preconditions* and *Quantity Conditions*, and new knowledge they introduce to the system description is presented in the slots *Relations* and *Influences* (see sections 4.3.5 and 4.3.6).

Simulation starts with the definition of the initial scenario. The simulator selects applicable model fragments in the library, computes their effects and creates representations for the states of the system. The algorithm may be summarised as follows:

a) An initial scenario sets the initial conditions of the system.
b) The simulator selects model fragments according to the conditions of the system, and creates a view and a process structure, which describes the state.

c) The effects of active processes are assessed. They are direct influences on some quantities, and indirect influences on other quantities.

d) The system might change because of process activity. A new set of values for the quantities is defined. It means that the current conditions of the system has changed.

e) Repeat step b; given the changes in the system, the simulator may create a view and process structure according to the new conditions of the system .

f) If more than one view and process structure are possible because of ambiguities, the simulator must try one of the following: ask the user for solutions, use additional knowledge from the knowledge base to solve the problem, or try all the possible alternatives.

g) Repeat steps b - f until no more changes are possible. Produce envisionment graph.

Part of the simulation described in section 4.2.7 can be used as an example of how this algorithm works. Consider a library with the views *Flowered Plant view*, *Pollinated Plant view* and *Plant with Fruit view*, and the processes *Pollination* and *Fruit production*.

Flowered Plant view and *Pollination* were already presented in sections 4.3.5 and 4.3.6, respectively. The other model fragments can be briefly described in terms of conditions and givens as follows (EnvironCond stands for 'environmental conditions favourable', and PhysioStimulation stands for 'adequate physiological stimulation'; SoilWater and Daylength not considered here):

Name	**Pollinated Plant view**
conditions	number_of (*Pollinated_Flower*) > 0 EnvironCond
givens	PhysioStimulation

Name	Plant with Fruit view
conditions	number_of (*Fruit*) > 0 EnvironCond
givens	there is object <u>child</u> number_of(*Child*) α_{Q+} number_of (*Fruit*)

Name	Fruit production process
conditions	number_of (*Pollinated_Flower*) > 0 EnvironCond
givens	there is object <u>fruit</u> there is quantity fruit_prod_rate I– (number_of (*Pollinated_Flower*) , A[fruit_prod_rate]) I+ (number_of (*Fruit*) , A[fruit_prod_rate])

This library may be used for answering questions like: 'What will happen in a scenario in which there are plants with flowers and favourable environmental conditions?' The simulation may be described as follows:

1) The initial scenario establishes the following conditions:

{ number_of(*Plant*) > 0 ; number_of(*Flower*) > 0 ; EnvironCond }

The qualitative simulator looks in the library for applicable model fragments. All are candidates, because all of them refer to the same object (<u>plant</u>) and favourable environment (EnvironCond). However, only *Flowered Plant view* is applicable, because of the inequality involving the number of flowers. So this model fragment is selected, and it introduces the following givens:

{there is nectar; there are insects; and the number of insects is related to the amount of nectar}

These elements satisfy the conditions for the model fragment *Pollination*, which is also selected. So the first state (state 1) is created with these two model fragments:

state 1 = {*Flowered Plant view*, *Pollination process*}

2) At this point, comes the analysis of what is happening within the state. First, the direct effects of the processes must be evaluated. Next, these effects propagate to indirect influenced quantities. Only *Pollination* is active, and its effects are:

{it creates new object pollinated flower; causes number of(*Pollinated_Flower*) to increase; causes number of (*Flower*) to decrease}

3) The system changes under the effects of this process. Now there is an object pollinated flower, and the number of (non-pollinated) flowers is decreasing. There is a feedback loop to control the process *Pollination* - it lasts while there are non-pollinated flowers (for the sake of simplicity, this last point will not be considered here).

4) The givens for state 1 become conditions for other model fragments to apply. So the simulator scans the library again for active model fragments. *Pollinated Plant view* meets the conditions described above. It is then selected and introduces new givens to the state description:

{physiological stimulation (PhysioStimulation)}

The situation of the quantities described so far about state 1 are the conditions for *Fruit production process* to become active. These two model fragments define state 2:

state 2 = { *Pollinated Plant view*, *Fruit production process*}

5) Analysis of what is happening with the system during state 2 starts with the effects of active processes. *Fruit production process* introduces new givens:

{it creates the object fruit ; causes the number_of(*Fruit*) to increase; causes the number of (*Pollinated Flower*) to decrease }

6) The system changed again. Now there is an object fruit, and the number of pollinated flowers is decreasing. Another feedback loop controls the application of *Fruit production process*.

7) Given the final arrangement in state 2, the simulator does a new search in the library. The model fragment *Plant with Fruit view* is applicable and introduces the following givens:

{there is child ; number_of (*Child*) is influenced by number_of(*Fruit*) }

The system now consists of plants with fruits and children taking fruits. Given that there is nothing else in the library that can be applied to this situation, the simulation ends in state 3:

state 3 = {*Plant with Fruit view*}

This simulation produces the envisionment graph

Initial scenario ==> state 1 ==> state 2 ==> state 3

According to the simulation, the answer for the initial question may be 'Flowered plants may produce fruits and attract children for eating them'.

The example above shows that the view and the process structure may change in each state. They reflect the current conditions of the system, and the givens from each model fragment determine the conditions in the next state. State transitions require that the simulator calculate the values of the quantities according to the relations between quantities, and then examines the whole library, checking for compatible model fragments. These operations involve *influence resolution* and *limit analysis*, respectively. These topics will be discussed in the next two sections (4.4.2 and 4.4.3).

Apart from checking for coherency between the model fragments selected in each state, and for consistency with the previous state, qualitative simulators also have specific rules for controlling state transitions. Much of the knowledge encoded in these rules is domain independent and refers to the continuity and termination of simulations.

For example, rules defining that values in the QS cannot be skipped (see section 4.3.2) are of great importance for the continuity of the simulation. Rules saying that when a quantity has value zero, the object to which the quantity refers does not exist, are useful for defining conditions for the simulation to stop.

Domain knowledge may also be implemented this way. For example, a rule can be used to say that fruit production may exist when non-pollinated flowers do not exist anymore. These state-transition rules are not considered here in detail. The general principles for state-transition in qualitative simulation are discussed in de Kleer & Brown (1984), and details about how they can be implemented in a qualitative simulator can be found in Bredeweg (1992).

4.4.2 Influence resolution

As shown in the previous section, a crucial point in reasoning qualitatively about a system refers to the understanding of what is happening during the time in which a particular state holds. Given a view and process structures, state transition results from the calculations of qualitative values given a set of relations between the quantities in each state. Creation of the causal link between the quantities in a running model and calculation of their values is called *Influence Resolution* (Forbus, 1984).

In QPT the *sole mechanism* assumption (Forbus, 1984) defines where to start the analysis: direct influences must be assessed first, in order to determine the effects of active processes. Next, their effects will be propagated through qualitative proportionalities, to ascertain the behaviour of the dependent quantities. As a result, the derivatives of all quantities will either be determined or some ambiguity will arise.

When resolving the influences on a quantity Q there are three possible situations (see Forbus & de Kleer (1993), for details):

a) Q is not influenced at all. In this case, it remains unchanged (Ds[Q] = 0).

b) Q is directly influenced by one or more processes. The result depends on the signs of the influences and the values of the rates. If there is just one direct influence, or if there are more influences, but they have the same sign, then this sign will be the value of Ds[Q]. If the influences have different signs, then the result can be ambiguous.

For example, suppose the following relations hold in a certain state:

$$I+ (Q, R1) \quad \text{and} \quad I- (Q, R2)$$

The value of the derivative of Q depends on the values of the flows or rates (R1 and R2) and on the signs of their influences. As discussed in section 4.3.3, direct influences are combined by addition: if the values of both R1 and R2 have the same sign, the result is ambiguous. If they have opposite signs, the derivative of Q can be defined. For example,

If $R1 > 0$ and $R2 > 0$ then $D[Q] = ?$ (because R1 causes Q to increase and R2 causes Q to decrease).

If $R1 > 0$ and $R2 < 0$ then $D[Q] > 0$ (because a negative influence with a negative value (as R2) gives the derivative a positive value).

Ambiguity is very likely to arise in qualitative simulations. For example, any population is under the influence of processes with opposite effects (natality and mortality).

Ambiguity can be resolved using additional information obtained from the user or from other sources of knowledge available in the library. An alternative approach is trying all the possible values. This last approach is implemented, for example, in QPE (Forbus, 1990) and GARP (Bredeweg, 1992). First the reasoner assumes that $R1 > R2$ calculates the derivative and propagates the result to the other quantities. Next it considers $R1 = R2$, and consequently, the direct influenced quantity does not change. Finally, the simulator uses $R1 < R2$ and propagates the result to the other quantities. The result is branching in the envisionment graph. In many situations, it is desirable to reduce the complexity of the graph. For example, scaling up the size of the models and introducing more quantities may result in intractable simulations. Elimination of spurious behaviour (the representation of physically impossible states) and task-oriented approaches to envisionment are a concern for the QR community. DeCoste (1994) is an example of the latter in the context of QPT. For educational purposes, ambiguity may be interesting, as discussed in Chapter 6.

c) Q is indirectly influenced. As discussed above (section 4.3.3), if there is only one indirect influence then the sign of the derivative of the influenced quantity (Ds[Q]) can be easily determined. Influence resolution is more complex if there are two or more indirect influences acting on Q at the same time. Two indirect influences can have synergistic effects if either they have the same sign and the proportionalities are of the same type, or they have opposite signs and the functional dependencies also have opposite signs. In other cases the outcome is ambiguous, as shown in the following examples (Table 4.3):

Proportionalities	**Ds[Q1]**	**Ds[Q2]**	**Ds[Q]**
Q α_{Q+} Q1 and Q α_{Q+} Q2	+	+	+
Q α_{Q-} Q1 and Q α_{Q-} Q2	+	–	?
Q α_{Q+} Q1 and Q α_{Q-} Q2	–	+	–

Table 4.3 Examples of the effects of two simultaneous indirect influences on the same quantity (Q). Ambiguity is represented by the question mark (?).

Solving ambiguities in indirect influences is a difficult task, more difficult than in direct influence resolution. As mentioned above, direct influences combine by addition, and knowledge about the magnitude of the influencing quantities suffices for defining the final value of the derivative of the quantity influenced. This is not the case of indirect influences. Information about their relative magnitudes is not enough because the underlying function relating Q1 and Q2 to Q could be either a sum, a product, a trigonometric function, an exponential expression or something else, and all these types of mathematical equations can be captured as a proportionality.

However, there are two approaches for handling ambiguous situations involving proportionalities:
1) If the modeller has more information about the nature of the relationship between the influencing quantities, it can be used for writing qualitative equations (see section 4.3.4).
2) If there is knowledge about the strength of the influences, it can be encoded in the library as annotations in the proportionalities, as proposed by D'Ambrosio (1987).

Both possibilities are explored in models presented in Chapter 5.

It is assumed that no quantity can be directly and indirectly influenced at the same time (Forbus, 1984). From the mathematical point of view, a theory that allows such a situation would be inconsistent, because the same quantity would be calculated by using two different types of equations simultaneously. Moreover, the expression of causal relations would be completely spoiled, because the primary causes of change could not be determined by the primitives in the modelling language.

This section has showed that, given a view structure and a process structure, it is possible to establish the causal links between the quantities and to calculate their new values, through influence resolution. The result of this operation may or not change the view and process structures. This is worked out by means of *limit analysis*.

4.4.3 Limit analysis

As shown in section 4.4.2, changes in the values of the quantities may result in changes on the view and process structures. Determining these changes is called *limit analysis*. It involves the following operations:

1. Using the current values of the derivatives of the quantities, the movement of each quantity in its Quantity Space is determined.
2. Quantity Conditions of views and processes are checked with the new values of the quantities.
3. Views and processes are selected to compose a description of the system in the new state.

For example, in a certain state of the simulation described in section 4.4.1, *Flowered Plant view* is active, the number of flowers has value medium, and is decreasing, influenced by the pollination rate. In the next state, *Flowered Plant view* still holds. The view structure may not change, although the value of the number of flowers is now few, and decreasing. Then in the following state, number of flowers is zero, and the view is no longer active. Zero is a limit point (see section 4.3.2), and is related to a discontinuity in the system's behaviour. A description of this state will have the *Non-flowered Plant view* replacing the *Flowered Plant view*. The purpose of the limit analysis is to anticipate these changes in qualitative descriptions of the system.

Limit analysis depends very much on the meaning of the values represented in the QS (called *limit points* by Forbus (1984)). If they represent the behaviour of the system being modelled appropriately, the limits imposed on the structure of the model (views and processes) correspond to relevant changes in the behaviour of the system. Forbus & de Kleer (1993) point out that limit analysis closes the loop of the inferences needed for describing behaviour: Quantity Spaces determine the process structure of the system, which in turn determines the values of the derivatives of the quantities. This eventually changes values on the Quantity Spaces again.

If limit analysis is repeated over and over again, the result is a sequence of qualitative states showing how the system evolves over time, that is, the behaviour of the system.

4.4.4 Time

To represent how the system evolves over time, Forbus (1984) proposes the use of *histories*. This notion was developed by Hayes (1979; 1990a; 1990b) to represent events that are spatially bounded but temporarily unbounded. Histories consists of *episodes* (which occur over intervals of time) and *events*, which bound episodes and always last for an instant.

The history of an object includes the history of its quantities (how they change), the history of the processes it is involved in, and the history of the views used to describe the situations the object had been involved in. The temporal extent of a view or process episode is the maximal time during which they are active. The spatial extent is the spatial extent of the individuals involved in the view or process.

As pointed out by Forbus (1990), the advantages of using this approach are that, being spatially bounded, histories may refer to descriptions that evolve locally. Thus, there is no requirements for simulations of other parts of the system. Being temporally extended, it is possible to follow what is happening with the objects during some action. Different objects interact if their histories intersect, that is, if there is a piece of state-time common to these objects.

Underlying to the notion of histories, Forbus (1984) uses Allen's interval-based temporal logic (Allen, 1990). Given that histories are idealised as contiguous blocks of space-time upon which reasoning can be organised, each temporal interval can be seen as one dimension of a history. This approach allows for making references to time intervals in the histories that, for example, *start-together*, *finish-together*, *meet*.

Although the simulations with the models described in this thesis can be seen as histories, and some initial explorations of comparisons between different states using Allen's temporal logic have been done, a detailed representation of the temporal aspects of ecological systems is beyond the scope of the present work.

4.5 How to implement it: guidelines for building qualitative models

This section discusses some guidelines for the modelling process. Modelling has been seen as an important issue in itself. However, there are no strict rules to follow, particularly in qualitative modelling. Part of the material discussed here was presented in Salles & Bredeweg (1997). Initially, some issues related to how to approach the domain knowledge in order to split the domain in a sensible way are discussed. Next, an overview of the problems related to the task of building a library is presented. Ontological commitments have to be made early in the modelling process. Next, the main representational aspects are discussed. Finally, the simulation itself has to be controlled, to avoid combinatorial explosion, and to keep the envisionment an acceptable size for the students.

4.5.1 The domain knowledge

Building qualitative models for simulations and explanations in an educational context is a two step process: it involves both fragmentation and re-construction of the domain knowledge. These two steps can be explained as follows:

The modelling activity starts with **the fragmentation of the whole domain** into parts that represent relevant concepts for the educational process. The ontological decisions required during the fragmentation of the domain knowledge are guided by the chosen QR formalism.

This fragmented knowledge will be organised into libraries of (more or less independent) model fragments. The modeller must then design **a representation of the re-constructed domain**, to show an idea of how the models map to the knowledge we want to communicate to the students.

Guidelines for this initial task of organising the knowledge to be represented in the models are hard to formulate. There is a domain independent component in this task. For example, we may start with some general aspects, and further move into more detailed representations of the system. However, the organising principles are to be found in the domain knowledge itself. We suggest that the initial task in building qualitative models is to **decide on the adequate conceptual units in the domain.**

In physics, liquid and heat flows, valves, and transistors are examples of these units. In ecology and in other important areas of biological research, such as genetics and evolution, <u>population</u> is one of the most important conceptual units.

4.5.2 On building the library

As discussed in section 4.4, domain theories are implemented as libraries containing sets of model fragments. The design of these model fragments is therefore an important step for building the libraries.

Given that we are interested in building models to support explanations in educational contexts, the concepts that constitute the domain knowledge have to be clearly represented. We assume that each model fragment must represent a relevant concept. This is called the **'One concept, one model fragment rule'**. According to this rule, a good approach is to split the knowledge into chunks that are relevant for the purposes of the model, and represent them as independent model fragments. Consequently, model fragments represent 'stand alone' concepts the student should master about the domain. For example, a model fragment defines a population, while natality, mortality, immigration and emigration are represented in different model fragments. This approach to the modelling process makes the library clearly organised, and facilitates the use of model fragments to support explanation (Chapter 7).

We have to **build the library as an incremental activity** around these conceptual units. The modeller starts with a core of model fragments, representing these basic conceptual units. More complex models involving more complex concepts are built upon these units.

Following the 'one concept, one model fragment' rule and building the library incrementally, soon the modeller has in the library **a kernel of model fragments representing key concepts**. The library will then expand around them, and more details about the concepts may be encoded. In the models of the cerrado vegetation we want to build, for example, population is the key concept. Accordingly, we started the libraries with a kernel of partial models about populations and the basic processes affecting them. As will be shown below, these models were used for representing the communities in different situations (Chapters 5 and 6).

This approach ensures that the number and the complexity of running models increases as the library grows. Bigger libraries require the addition of less model fragments in order to increase the number of running models.

And what sort of vocabulary do we need? Choosing an ontology is a crucial point in building the qualitative models. The ontology will provide the perspective for the conceptualisation of the domain, and the vocabulary for the interaction with the students.

4.5.3 The ontological commitments

The ontology developed in QPT is built around the notions of objects, views and processes. However, some problems remain. How should the objects in the world being modelled be characterised? We suggest that this processes of **individuation must be based on permanent characteristics of the objects**. Changeable properties, particularly those that vary continuously, change because active processes are affecting them either directly or indirectly.

Simple models about populations can be developed around the notion that populations can be represented a pool of individuals that can be affected by flows of born, dead, immigrated and emigrated individuals. This approach is similar to the 'contained stuff' ontology developed by Hayes (1979; 1990b) and used by Collins & Forbus (1989) to build their library about thermodynamic processes. The population is seen as a 'container', in which individuals are flowing in (through natality and immigration) and flowing out (by means of mortality and emigration). The size of the population depends on its initial size and on the balance of these flows.

The use of the 'contained stuff' ontology is acceptable here because populations have the following properties:

a) A population is defined in terms of a group of individuals of the same species living in the same area during a certain period of time. In this sense, the population can be spatially defined. It is fair to think about a population as being an entity, although all the individuals might have changed, just as a river is a river contained by its banks, even though all the water changes.

b) Some organisms can easily be recognised as individuals, such as human beings. However, in organisms such as bacterias, fungi and many plants, the notion of 'individual' is not clear. In fact, identifying individuals is one of the most difficult problems in studies of the cerrado vegetation. Often cerrado plants have some underground connection that can only be seen when the root system is exposed. It may happen, for example, that the above ground parts of trees are several meters distant, although they are linked by the root systems. An alternative representation in these cases is to consider the mass of individuals as if they were just one.

c) It follows from the previous item that populations can be seen either as groups of separate individuals or as a mass of individuals. The size of the population can be represented respectively by the 'number of individuals' or by the 'amount of biomass' of the individuals. The choice depends on the type of organism, and on the purposes of the model. For example, when the problem solving activity requires just counting the individuals, in spite of their size or other particular attributes, then the 'number of' approach is adequate. When the size of the individuals is an issue, such as in studies about the energy flux (photosynthesis, respiration), the 'number of' representation is inadequate, because it cannot capture the differences between the individuals with respect to the metabolic activity. In these cases, the 'amount of' representation is more useful.

d) The 'number of' and the 'amount of' representations are interchangeable. Ecologists often refer to population size by means of density, and it is assumed that there is a correspondence between the number of individuals/space and the biomass/space.

In educational contexts, the 'number of' representation is often the first to be presented, maybe because it is closer to the common-sense of the students. The 'amount of' comes later, when required by the curriculum. Given that population can be seen in these two ways, and that they are interchangeable, it is assumed that the 'contained stuff' ontology can be taken as the basis for the models described in this thesis.

As in other qualitative models built according to QPT, quantities represent continuous properties that change over time. The values they can take on are represented in Quantity Spaces. In some sense, QS tell the story of the quantities, and one can figure out the most relevant properties of some object by inspecting the QS of its quantities.

Given the limitations of qualitative representations, **only interesting values must be represented in the quantity spaces.**

Reality is complex, and models also tend to be very complex. But there is a limit to the amount of variation that can be handled by a student - too much variation makes the model difficult to understand. Adding a new quantity to the model, or an extra value to its QS can make the model and the simulation much more complex. There are more calculations to be done, more alternatives to be considered, more ambiguities to be solved. The modeller should build quantity spaces that facilitate the generation of all the qualitative states relevant to the system at hand, but that still keep the simulation manageable. Variation must be kept at the minimum required by the purposes of the model. We refer to this as being the **'Minimum Required Variation' rule**.

This rule can be implemented in different ways:

a) We can focus on deviations from a certain 'standard value'. This is specially useful in situations in which the notion of equilibrium is important, and a QS such as {below normal, normal, above normal} can be used. The links between a QS with 'absolute' and a QS with 'relative' values can be implemented by means of correspondences. Values such as low and very low, for example, can be considered below normal. This will reduce the variation represented in the model, while retaining the semantics of the quantity values.

b) We can assign bigger QS to quantities that are more important for the model's purposes, and smaller QS to quantities of secondary importance. For example, if the purpose of a model is to represent the environmental influences on germination, the number of germinated seeds can have a QS = {zero, small, medium, large, very large}, whereas the other quantities (litter, temperature, light) have QS = {plus}.

c) We can use inequality statements to express diversity among quantities that have quantity spaces with a single value. For example, the number of plants in two populations can have QS = {plus}, but it is possible to represent in the model the fact that one is 'greater than' the other.

In all these cases the resulting models capture a more focused vocabulary about the relevant quantities and how these may vary. This makes a model easier the students to be understand.

As already discussed in section 4.3, we assume that **only processes can change the values of quantities**. According to QPT, changes start under the direct influence of processes, and then propagate through qualitative proportionalities. It is a convenient assumption: if the value of some quantity is changing, it is a direct or indirect consequence of some active process.

Some processes are not difficult to characterise. For example, there is no problem in recognising the effects of the mortality process. However, there are ecological processes which involve several quantities and influences, and their representation can become very complex. Consider, for instance, the notion of 'conservation' applied to the management of ecosystems. It involves many mechanisms, influencing several different objects and quantities. Actually, we can imagine conservation as a set of processes causing changes in the ecosystem in the same direction.

Representing the details of complex processes such as conservation has the potential to bring more problems than benefits, both for the modeller and for the students exploring the models. Simulations may become less attractive or even clumsy, with an overwhelming amount of detail to be grasped. The representation of processes in qualitative models can be simplified by using different approaches:

a) **Processes can be organised in a structured way**, by using an *isa* hierarchy, for example. This approach will support utterances such as 'colonisation is a kind of immigration process that occurs when there's no population in a certain area'.

b) **Processes can be aggregated** to represent a sum of processes that occur at a lower level (cf. section 4.3.6). Aggregated processes may have a special meaning and involve specific vocabulary. For example, natality, mortality, emigration and immigration can be aggregated into a single process, population growth. At least in certain cases, aggregation of processes can be related to the scaling problem. In the example given here, natality, mortality, and migration are phenomena that affect individuals, whereas population growth has no meaning at the individual level: it is a typical population level process.

c) **Some agent may be introduced in the model** to account for complex sets of processes that cannot be aggregated. Human actions, for example, have these characteristics. Processes such as conservation and degradation are very complex and involve many mechanisms of change in the ecosystem including psychological, anthropological, economic and social effects. Instead of aggregating all these components, it is easier to introduce an agent (e.g. a human action) that produces the same effect.

4.5.4 The simulation

Learning environments may be made more efficient by **providing interactive simulations**. In an interactive simulation, students can change the conditions of the system being simulated. For example, students may want to define different initial scenarios. Also, they may want to pose questions and receive explanations about the system being modelled and the results of the simulations. Finally, interactivity includes some sort of control over the simulation, so they can guide it in the direction they want. These points will be discussed in Chapter 7.

In an educational context there is a limit to the number of states that can be dealt with by the student - both understanding and motivation become problematic if the number of states is too high. The modeller has to look for means to **simplify the simulations**.

Simplifications can be done at the level of the domain knowledge. Leaving out some details from the model is the most obvious option. For example, if we do not take into account the age structure of the population or its spatial distribution, simulations about the population behaviour will be much simpler. Some points discussed before, such as using different quantity spaces for different quantities, may also simplify the simulations.

Two other simplification mechanisms can be used: a) create model fragments which implement simplifying assumptions, and b) focus the simulation on the most relevant state transitions.

Using model fragments as simplifying assumptions is a solution for keeping using detailed model fragments in complex scenarios, while taking a more abstract view of the system.

A more abstract or simplified view of the system can be achieved by **using model fragments that implement simplifying assumptions** about the domain. For example, the library includes model fragments about natality, mortality, immigration and emigration, and the population growth process can be defined as a combination of these basic processes. A possible simplifying assumption is to assume that the population does not have migratory movements (it is a closed population), and therefore population growth is defined as a combination of natality and mortality. This effect can be achieved by creating a model fragment defining 'closed population'. In a simulation where it is assumed that the population is closed, immigration and emigration will not be taken into account.

Some state transitions may be very unlikely to happen, given constraints put by the domain knowledge. Termination rules can be used to reduce the number of possible states by removing terminations with low probability. These **focused state transitions** reduce the number of possible terminations the qualitative simulator has to consider at each state transition. Note that, as in the previous case, the set of model fragments in the library remains the same, and the number of branches in the simulation is explicitly reduced. For example, suppose that in a simulation involving a population the mortality rate is decreasing. The simulator will consider the possibility of having the number of dead equal to zero. However, this is very unlikely to happen. We can remove this possibility by introducing into the library a model fragment with a rule saying that while there is a population, the number of dead cannot be zero. Similarly, dedicated termination rules could be used for selecting more likely state transitions. This approach however was not taken in the work described in this thesis.

4.6 Conclusions

This chapter has discussed the fundamentals for building qualitative ecological models that can be used to support simulations and explanations in learning environments. These fundamentals include the ideas we want to communicate, the language for representing these ideas, and how to implement them in computer-based learning environments. This chapter is therefore, the basis for the models and the simulations described in Chapters 5 and 6, and for the explanations that can be generated from them, presented in Chapter 7.

A domain theory of vegetation dynamics was developed to support the construction of qualitative models representing the ecology of fire in the cerrado. The main points discussed were as follows:

a) Population is the basis for representing changes in the vegetation.

b) The central issue in any theory of population dynamics is how to represent variation;.

c) The quantities included in the model can have some measure of their variation (derivative) calculated either explicitly or not. The derivatives of the most relevant quantities must be explicitly calculated.

d) There are four basic population processes: natality, mortality, immigration and emigration. They are the ultimate cause of changes in the population size.

e) Qualitative models have to include particulars of these basic processes, such as considering natality as a combination of flowering, pollination and germination.

f) Environmental influences must be explicitly represented in the qualitative models, since they are the most common reason for changes in the populations.

g) The objects involved and the situations that best describe the behaviour of the populations and the conditions for the processes to happen must also be explicitly represented in the models.

h) The domain theory of population dynamics can be extended to incorporate theories of communities and ecosystems.

In order to organise the discussion about the models developed to represent these ideas and the modelling process itself, we proposed a framework in which the physical structure of the system is decomposed into concepts, causal relations and mathematical operations. The conceptual structure includes knowledge about objects, quantities, quantity values, and quantity relations. It also includes descriptions of the situations and the mechanisms of change. The causal structure is a representation of how changes start and propagate within the system. The mathematical structure is a description of the constraints between quantities and of the procedures to calculate their values.

This framework can be implemented by using the modelling primitives available in QPT and SIMAO. The former is an ontology developed to represent the conceptual and the causal structures of the system, which offers a weak representation of the mathematical structure. SIMAΘ provides a qualitative algebra that can be used to implement the qualitative equations that constitute a detailed description of the mathematical structure. Combined, these two modelling formalisms can be used to implement models designed to support simulations and explanations.

The normalisation of the modelling process is a goal to be achieved both for the QR and the ecological modelling communities. The chapter concluded with some guidelines for building qualitative models. These guidelines focused on the fragmentation of the domain knowledge, the construction of the library, the ontological commitments and the control of the simulations.

In the next three Chapters (5, 6 and 7), the models developed according to the fundamentals discussed in this chapter are described. In Chapter 5, the mathematical structure is the basis for the simulations. For simulations with the models described in Chapter 6, the basis is the causal structure. Finally, the conceptual structure, along with the mathematical and the causal structures are explored as a basis for explanation generation in Chapter 7.

Chapter 5. Simulation models based on the mathematical structure of the system

Within the framework discussed in Chapter 4, the structure of the system we want to model can be analysed in terms of concepts, causal relations and mathematical relations. The conceptual structure includes descriptions of the objects, quantities, situations and mechanisms of change. The causal structure represents the origin of changes in the system, and their propagation to other parts of the system. Finally, the mathematical structure describes the constraints between the quantities and how to calculate their values.

In qualitative models designed to support simulations and explanations in learning environments, these structures play different roles. On the one hand, the conceptual structure is essential for explanations, and less important in supporting simulations. On the other hand, the mathematical structure is essential for simulations, but has little to offer the automatic generation of explanations. The causal structure is important in supporting explanations and for simulations. It is particularly important in simulating the dynamic aspects of the system, combined with the other two layers. These aspects will be explored in the next three chapters (5, 6, and 7).

The basis for the models discussed in this chapter is a detailed representation of the mathematical structure of the system. Changes of state are explained in terms of changes on the values of the magnitudes of the quantities, calculated by means of qualitative equations. In Chapter 6, the focus is on the causal structure. There, changes of state are analysed in terms of the propagation of influences, and assessments of the values of the derivatives. Finally, Chapter 7 discusses how the conceptual structure provides support for the automatic generation of explanations about the simulations and the models described in Chapters 5 and 6.

This chapter starts with a quantitative model of an ecological problem, which provides the baseline for the development of qualitative representations of the same problem.

Next, three qualitative models are described, introducing the representation of the mathematical, the causal and the conceptual structures of the system. Finally, further problems are discussed within the context of a model of the establishment of cerrado plants. Table 5.1 summarises the problems these models deal with, the modelling framework used, and the section in which the model is discussed.

model	**the problem**	**framework**	**section**
Life cycle I	to calculate population size given initial number and intermediate variables	SD	5.2
Life cycle II	to calculate population size in the next time step, and compare results obtained with the SD model	SIMAO	5.3
Life cycle III	to calculate population size with a representation of the population dynamics based on a single process	QPT + SIMAO	5.5
Life cycle IV	to calculate population size with a representation of the population dynamics based on multiple processes	QPT + SIMAO	5.6
Establishment	to calculate the value of establishment rate representing non-monotonic relations and ambiguous situations	QPT + SIMAO	5.7

Table 5.1 A summary of the models presented in Chapter 5.

The chapter is organised as follows:

In 5.1 an ecological problem involving some aspects of the impact of fire and other environmental factors on the life cycle of a plant population is presented. The problem is tackled using three different modelling approaches in the series *Life Cycle I - IV*, and provides the background for the comparison of qualitative models with quantitative models.

The first model, *Life Cycle I*, represents the problem using the System Dynamics (SD) framework (Forrester, 1961). The system is conceived as a combination of compartments and flows, and a set of mathematical equations describes the constraints between the quantities (section 5.2). Next, in the model *Life Cycle II* (section 5.3), the mathematical equations are translated into qualitative equations using the algebra developed in SIMAO (Guerrin, 1991; 1992). Consequently, the SD model *Life Cycle I* and its SIMAO equivalent (*Life Cycle II*) have many similarities. They encode respectively a quantitative and a qualitative mathematical representation of the same mathematical structure of an ecological system.

Do these models produce similar results given similar initial scenarios? In order to answer this question, an experiment was designed to compare the output of the two models. The criteria for evaluation and the results of the comparisons are presented in section 5.4.

Whereas in *Life Cycle II* only the mathematical structure of the system is represented, the model *Life Cycle III* (section 5.4) introduces the causal and the conceptual structures of the system. Objects, views and processes are related to the mathematical structure already developed in the SIMAO model. In this way, many aspects of the system that were implicit in *Life Cycle I* and *Life Cycle II* became explicit in *Life Cycle III*.

The last model of the series, *Life Cycle IV* (section 5.5) represents an alternative approach to *Life Cycle III*. Using the same set of qualitative equations, population growth is disaggregated into other processes, namely flowering, seed production, germination, establishment and mortality. Given that the notion of process is central in QPT-based models, this creates an opportunity for a more detailed representation of the model components. Since the three qualitative models (*Life Cycle II - IV*) are based on the same representation of the mathematical structure, the values calculated for the quantities in simulations are always the same.

Finally, the model *Establishment* (section 5.7) represents the survival of young plants under the influence of cover and time since the last fire. It is based on data obtained in scientific research, and illustrates two aspects that were not discussed in the previous models: handling non-monotonic relationships between quantities and ambiguous situations.

The implementation of the models *Life Cycle III*, *IV*, and *Establishment* is based on the same data structures used in GARP (Bredeweg, 1992), and presented in the Appendix. This way, a unique machinery could be used for deriving explanations from these models and the models implemented in GARP described in Chapter 6. However, these models were not implemented in GARP, but as separate Prolog programs.

5.1 A plant's life cycle: an ecological problem to be modelled

Suppose there is a plant population in the cerrado with the following characteristics: flower production is influenced by the number of plants and by the occurrence of fire events. The production of seeds is influenced by the number of flowers and by some genetic factor that determines the number of seeds per flower. The number of seeds, temperature and soil water influence the number of germinating. The number of germinated seeds and the size of the population determine the establishment of new plants, and the mortality is influenced by the size of the population and by soil water. The influence diagram in Figure 5.1 summarises these relations:

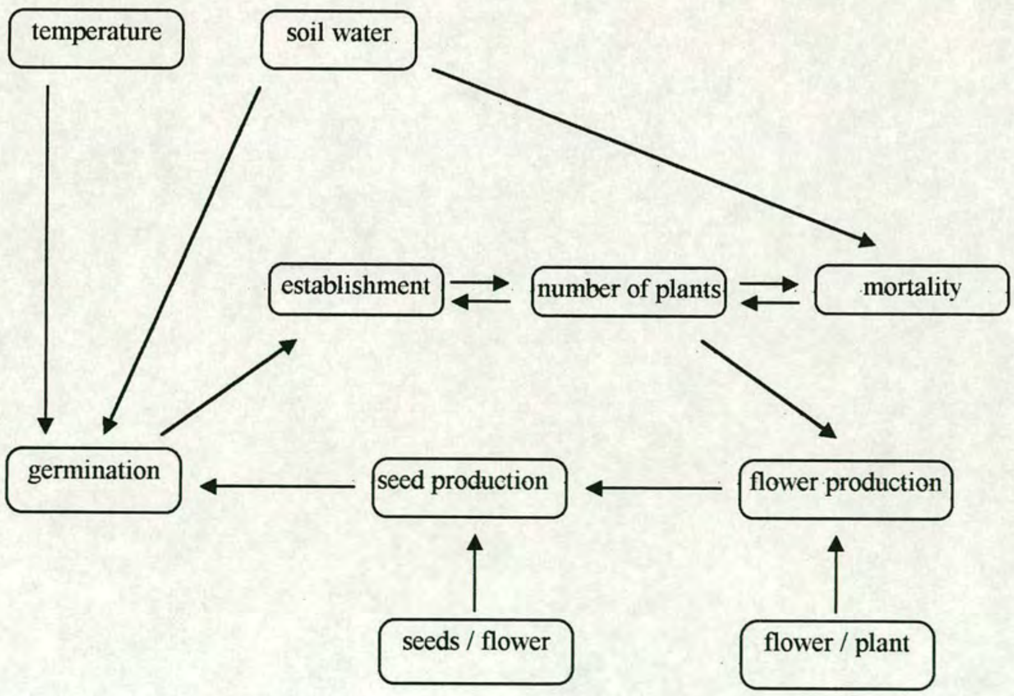

Figure 5.1 Influence diagram representing a plant's life cycle.

The relations described above provide the elements for the solution of the following problem:

> Given the initial number of plants in the population and information about the occurrence of fire events, soil water and temperature, what is the number of plants in the next time step?

This problem is often mentioned in studies about the effects of fire on the vegetation. Both in the interviews and in the literature (cf. Chapter 3), flowering, germination and establishment are often used to account for specific behaviours of plants in cerrado.

With respect to the effects of fire on flowering, three different behaviours are observed in cerrado plants:
a) plants insensitive to fire produce roughly the same number of flowers regardless of fire events;
b) plants sensitive to and negatively influenced by fire produce fewer flowers after fire events;
c) plants sensitive to and positively influenced by fire produce more flowers after fire events.

The number of seeds produced per flower may also vary. Three possibilities are observed:
a) plants that produce roughly one seed per flower;
b) plants that produce a few seeds per flower;
c) plants that produce many seeds per flower.

Combinations of these two properties account for a great deal of the variation observed in cerrado plants. Although asexual reproduction is often observed in cerrado plants (for example, Coutinho, 1990), it is not represented here.

Germination requires some physiological stimulation, and is generally influenced by environmental factors. For example, it is accepted among Brazilian researchers that when the vegetation has fewer woody components, there is more light, temperatures are higher and there is less water on the ground, seeds of grass are more likely to germinate than seeds of trees.

Establishment is the survival of very young plants (seedlings). As discussed in Chapter 3, it is a crucial stage for plants in the cerrado, because the seedlings must be able to obtain their own resources. Considering that soils in the cerrado areas are poor in nutrients, competition between seedlings is common. Seedlings also have to resist environmental changes, such as a spell of dry weather during the wet season.

Mortality affects individuals differently at different stages in the life cycle. It tends to be higher in seeds and seedlings, and lower in adults (Ramos, 1990; Silva *et al.*, 1996; Sato & Miranda, 1996; Raw & Hay, 1985). Fire, soil conditions and parasitism have been identified as possible causes of mortality. In Figure 5.1 mortality is related to the number of plants and soil conditions: it is assumed that the drier the soil, the higher the mortality.

5.2 Life Cycle I: a quantitative model

In System Dynamics the system is represented as compartments that correspond to state variables, and flows between them. Dynamic aspects of each compartment are described by a differential equation. The model also includes intermediate variables, which are used to calculate the values of the flows, and constants (parameters), which are generally used to calibrate the models (Forrester, 1961). This section describes a System Dynamics model (Life Cycle I) of the problem stated in section 5.1.

The model was built in FloMo, a modelling environment developed for educational purposes by Robert Muetzelfeldt at the University of Edinburgh. In FloMo, students can create their model and run numerical simulations without entering differential equations directly, only the equations needed for each flow. Figure 5.2 shows the model Life Cycle I.

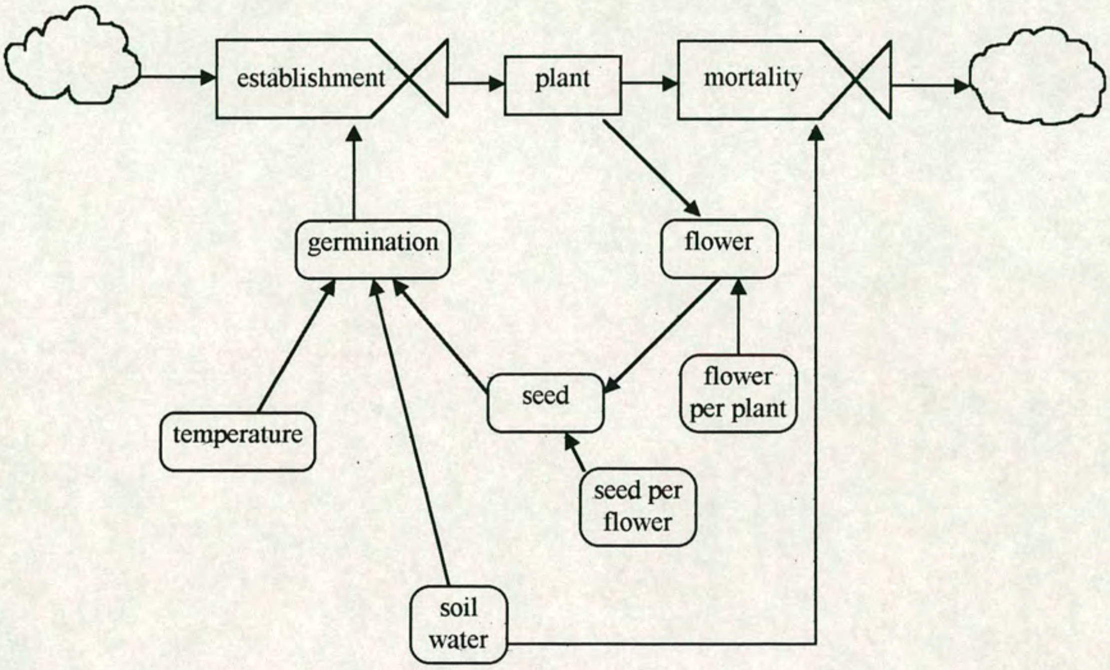

Figure 5.2 A System Dynamics model.

Life Cycle I consists of one state variable (number of plants), three intermediate variables (number of flowers, number of seeds, number of germinated seeds), four parameters (average number of flowers per plant, average number of seeds per flower, the effects of soil water and the effects of the temperature), an inflow (establishment) and an outflow (mortality). This model is not based on actual data, and the values for the parameters were chosen intuitively. The modelling components of Life Cycle I are shown in Table 5.2:

SD primitive	model element	how to determine the values
State variable	number of plants	plant = $plant_0$ + (establish – dead)
Flow	number of established plants	establish = germ * 0.7 * (1 + 1/plant)
	number of dead plants	dead = plant * 0.1 * (1 – soil)
Variables	number of flowers	flower = plant * typef
	number of seeds	seed = flower * types
	number of germinated seeds	germ = seed * temp * soil
Parameters	number of flowers per plant	typef = a multiplier between 1 and 3
	number of seeds per flower	types = a multiplier between 1 and 3
	availability of soil water	soil = a multiplier between 0.10 and 0.90
	temperature	temp = a multiplier between 0.10 and 0.90

Table 5.2 Modelling components of the model Life Cycle I.

The model is instantiated by assigning an initial value to the state variable (plant) and values to the parameters. The latter are used to represent species-specific characteristics determining flower and seed production, and the influences of soil water and temperature. To calculate the number of flowers, the number of plants is multiplied by a multiplier, typef, the value of which depends on the plant's sensitivity to fire. For example, if there is no fire event or the species is insensitive to fire, then typef =2. If there is a fire event and the species is sensitive and positively influenced, then typef = 3, otherwise typef = 1.

The number of seeds is calculated by multiplying the number of flowers by a factor that represents the number of seeds per flower (types). The student can assign values between 1 and 3 to represent, respectively, species that produce a small, a medium or a large number of seeds per flower. The other parameters are assigned to represent the amount of soil water and the temperature. If, for example, we want to increase the amount of water in the soil or the temperature on the system, then we increase the values of these parameters. The values of the state variable, intermediate variables and parameters have a correspondence with the values used in qualitative models (cf. section 5.3).

The simulation then runs forward iteratively in time steps of one year. The results obtained with this model were subsequently compared with the corresponding qualitative model, and will be discussed in section 5.3.

5.2.1 Some comments about the compartment-flow model

1. In accordance with the framework discussed in Chapter 4, the conceptual structure of the system is not explicit in this model. There are no clues in the model itself about objects, process and situations.

2. The causal structure is also not explicit. At least in this quantitative model, the relations between the quantities do not specify the direction in which changes are propagated. Lack of explicit conceptual and causal structures are a shortcoming of using this model to support automatic generation of explanations.

3. The mathematical structure of the system is well represented in the model. However, in contrast with the qualitative models, it does not change during the simulation (cf. Chapter 6).

4. Modularity is achieved by using separate equations to calculate the values for the quantities. The modeller could change any of them, if necessary, and then proceed to re-run the whole model.

5. Although a very simple model, Life Cycle I illustrates the main features of the compartment-flow modelling paradigm. In this approach, conceptualisation of the problem being modelled[21] is supported by the graphical representation of the model components.

5.3 Life Cycle II: translating quantitative into qualitative equations

One of the aims of this (5.3) and the following section (5.4) is to present a direct comparison between quantitative and qualitative modelling of the same ecological problem. One possible qualitative modelling approach is that of SIMAO (Guerrin, 1991; 1992). This section describes a model of the problem presented in section 5.1 built within this formalism (*Life Cycle II*).

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[21]The compartment - flow modelling paradigm is called 'qualitative modelling' by Haefner (1996). This is not how this term is used in this thesis (cf. chapter 2).

Knowledge in SIMAO is organised around the notion of Knowledge Units. They encode procedures to assign values to the quantities, given observations expressed in linguistic terms or qualitative equations. Since there is no representation of any other modelling component in the SIMAO formalism, the model *Life Cycle II* is only built around quantities and constraints. In order to compare this approach with SD, it was designed to be as similar as possible to the numerical model described in section 5.2.

5.3.1 Quantities and quantity spaces

Each quantity is associated with a set of possible qualitative values, its Quantity Space (QS). The typical QS in SIMAO consists of five intervals represented by the symbols {pp, p, m, f, ff }. This QS is completely ordered. Therefore,

$$pp < p < m < f < ff$$

This QS is used for most of the quantities in the model. For some quantities, only part of this QS was used, for example, {m, f, ff }. In these cases, the qualitative algebra developed in SIMAO can be used. However, the qualitative algebra does not deal with zero and negative values. These are important values for some quantities, such as <u>growth rate</u>, a quantity introduced in the model for representing variation, as in the SD model. Therefore these quantities cannot be involved in direct calculations, and their values have to be assigned by different mechanisms. The quantities involved in the model *Life Cycle II* and their QS are shown in Table 5.3:

Quantities	Quantity Space	QS-symbols
number of plants, number of flowers, number of seeds, number of germinated seeds, number of established plants, number of dead plants, number of plants next time unit	{very_few,few, medium, many,very_many}	{pp,p,m,f,ff}
soil water	{very_dry, dry, medium, wet, very_wet}	{pp,p,m,f,ff}
temperature	{very_cold, cold, mild, hot, very_hot}	{pp,p,m,f,ff}
number of flowers per plant	{small, medium, large}	{m,f,ff}
number of seeds per flower	{small, medium, large}	{m,f,ff }
growth rate	{minus, zero, plus}	{– , 0, +}

Table 5.3 Quantities and their respective values included in model *Life Cycle II*.

As discussed in Chapter 2, the procedures for calculating the values of the quantities in SIMAO are described by means of *Transfer Rules* and *Action Rules*.

Transfer Rules describe how to assign values to quantities. They can be of two types, TR-o and TR-q:

a) TR-o is used for the translation of observations expressed in linguistic terms into qualitative values. For example, if the soil is dry, then the quantity <u>soil water</u> has value <u>p</u>.

b) TR-q consists of qualitative equations used to calculate the value of a quantity from the values of other quantities.

In the model *Life Cycle II*, TR-o are used to assign values to quantities that are input to the simulation. The other quantities are calculated by using TR-q.

When more than one Transfer Rule is available to calculate the value of a quantity, Action Rules are used to control the application of the Transfer Rules. Action Rules are not necessary in *Life Cycle II*, because there is only one Transfer Rule for each quantity.

5.3.2 The Knowledge Units

There are 12 Knowledge Units in *Life Cycle II*, designed to calculate the value of each quantity. Of those, five are TR-o designed to translate input values for the number of plants, number of flowers per plant, number of seeds per flower, temperature and soil water. In addition, seven TR-q are used to calculate the values of number of flowers, seeds, germinated seeds, established plants, dead plants and plants in the next time unit.

The qualitative algebra described in Chapter 4 (section 4.3) was used to write the equations for the TR-q. As mentioned before, these equations were kept as close as possible to the equations used in the quantitative model (section 5.2). Some elements cannot be captured directly and in these cases some sort of qualitative interpretation of the rationale behind the mathematical equation is required. For example, how should the number of dead plants be calculated?. Table 5.4 presents the two approaches:

Equation to calculate mortality in the numerical model (*Life Cycle I*)	Transfer rule to calculate the number of dead plants in the qualitative model (*Life Cycle II*)
dead = plant * 0.1 * (1 – soil)	equation([Plant, SoilWater, Dead]):- decr2(Plant, Dec2Plant), inv(SoilWater, InvSoilW), mult(Dec2Plant, InvSoilW, Dead).

Table 5.4 How to calculate the number of dead plants in the quantitative and in the qualitative models.

In the quantitative model, the number of dead plants is calculated by multiplying the number of plants by a constant (0.1) and by a parameter representing the effect of soil water. The rationale behind this calculation is that there is a natural mortality that varies according to the soil water. The value of <u>soil</u> ranges between 0.1 and 0.9. Higher values of this parameter correspond to less plants dying, because it enters the equation as (1 – soil). This parameter represents the amount of water and its effect on the mortality. In the worst conditions, some 9% of the individuals may die. This is an acceptable prediction for cerrado plants (cf. Chapter 3).

Mortality is represented intuitively in the qualitative model by decreasing in two steps the value of the quantity <u>plant</u> (Plant) in its QS, leading to an intermediate quantity (Dec2Plant). The quantity that represents the amount of water in the soil (SoilWater) has to be inverted to capture the notion of a negative influence: more water means less mortality. The multiplication of the two intermediate values (Dec2Plant and InvSoilW) gives the number of dead plants (Dead).

The Table 5.5 presents all the TR-q implemented in *Life Cycle II*:

Objective of the Knowledge Unit	**Tranfer rules**
to calculate the number of flowers	equation([Plant, Typef, Flower]):- mult(Plant, Typef, Flower).
to calculate the number of seeds	equation([Flower, Types, Seed]):- mult(Flower, Types, Seed).
to calculate the germinated seeds	equation([Seed, Temperature, SoilWater, Germ]):- mult(Seed, Temperature, IntermVal), mult(IntermVal, SoilWater, Germ).
to calculate the dead plants	equation([Plant, SoilWater, Dead]):- decr2(Plant, Dec2Plant), inv(SoilWater, InvSoilW), mult(Dec2Plant, InvSoilW, Dead).
to calculate the established plants	equation([Plant, Germ, Establish]):- inv(Plant, InvPlant), decr1(Germ, Dec1Germ), mult(InvPlant, Dec1Germ, Establish).
to calculate the growth rate	equation([Establish, Dead, positive]):- Establish greater_than Dead.
to calculate the population next time unit	equation([Plant, positive, NextPop]):- incr1(Plant, NextPop).

Table 5.5 Knowledge Units representing the rules (TR-q) used in model *Life Cycle II*.

Note that the Knowledge Units for calculating growth rate and population in the next time unit have three interpretations (positive, zero, and negative), and only one is presented in the Table 5.5 as an illustration. The general rules for them are, respectively,

equation([Establish, Dead, GrowthRate])

and

equation([Plant, GrowthRate, NextPop]).

Growth rate can be negative, zero or positive. However these values cannot be calculated directly with the algebra used in this model. They are obtained by comparing the number of established plants with the dead plants. For example, growth rate is positive when established is greater than dead. The value of growth rate is input to the following equation, and causes the population to decrease, remain steady or increase in the next time unit. Continuing with the example, a positive growth rate causes the number of plants to increase one step in the next time unit.

5.3.3 Results obtained with Life Cycle II

A selection of the most representative results obtained in simulations with the model *Life Cycle II* is presented in Table 5.6. The first five columns represent the inputs: number of plants, flowers and seeds per plant, soil water and temperature. The last two columns show the calculated values of growth rate and of the number of plants in the next time unit.

number of plants	flowers per plant	seeds per flower	soil water	temperature	growth rate	plants next time
pp	m	m	pp	pp	0	pp
				p	0	pp
				m	0	pp
				f	0	pp
				ff	+	p
	ff	ff	pp	pp	0	pp
				p	0	pp
				m	+	p
				f	+	p
				ff	+	p
m	f	ff	p	pp	–	p
			p	p	0	m
			p	m	+	f
	ff	f	p	pp	–	p
			p	p	0	m
			p	m	+	f
ff	ff	f	ff	p	0	ff
			ff	m	+	ff

Table 5.6 Some results obtained in simulations with the model Life Cycle II.

There are some aspects of the results presented above which are worthy of note:

a) The smallest value in the QS for the number of plants is very few. It is assumed that there is always a population. Consequently, even in the worst scenario considered here (a population with very few plants, producing a small number of flowers per plant and seeds per flower, in a very dry and very cold environment), the population persists with very few plants. This is ecologically plausible since there are often microhabitats that enable plants to survive even under very adverse conditions.

b) The effects of the factors influencing flower production (typef) and seed production (types) are interchangeable. That is, combinations such as {typef = f ; types = ff} and { typef = ff; types= f} produce the same results. Table 5.6 shows this effect for a population with medium size.

c) Temperature can exert a strong influence on the number of plants in a scenario in which the population has very few plants (pp), producing a small number of flowers per plant and seeds per flower (m), and in which the soil is very dry (pp). A change in the temperature from hot (f) to very hot (ff) increases the number of germinated seeds. It causes the growth rate to become positive and the population to increase.

d) The number of plants in the next time unit is not calculated directly. As explained in section 5.3.2, it depends on the values of established and dead plants. Therefore, the possibilities for the number of plants in the next time step are: keep the initial value, change one step up, or change one step down in the QS. This follows the so called *continuity rule* (Forbus, 1984; de Kleer & Brown, 1984), which postulates that values in a QS cannot be skipped.

e) A very large population (ff) can still be increasing, but its qualitative value will not change. A change of temperature (from cold to mild or hotter than this) may cause this effect, when the soil is very wet (ff).

5.3.4 Some comments about the model Life Cycle II

a) Within the framework defined in Chapter 4, *Life Cycle II* has neither a conceptual nor a causal representations of the structure of the system. It has limitations for explanations, as will be discussed in Chapter 7.

b) The mathematical structure of the system is well represented within this modelling paradigm. The most important feature of this model is the qualitative representation of quantities and constraints between them. As shown in this section, some mathematical equations can be rewritten using SIMAO's qualitative algebra.

c) The qualitative algebra used here enables the processing of heterogeneous variables. As pointed out by Guerrin (1991), it is possible to combine variables that are not related by physical laws, but that are *de facto* associated in expert reasoning, such as the external aspect of the soil and the amount of water in it.

d) The vocabulary used to represent quantities and their values is very close to the language used by students. So are the qualitative operations to combine them, for instance when adding <u>few</u> to <u>many</u> and still getting <u>many</u> as the result.

e) A limitation in the qualitative algebra is that it does not deal with zero and negative values. The only quantity in this model that has these values in its QS, <u>growth rate</u>, cannot be calculated directly.

5.4 Comparing the results of qualitative and quantitative simulations

This section presents a comparison between the results obtained from models *Life Cycle I* and *II*. For the purposes of this analysis, the results from the System Dynamics model (*Life Cycle I*, section 5.2) were taken as the "true" results, and the aim was to see whether the qualitative model (*Life Cycle II*) gave correct results, within the limits imposed by its QS. The methodology developed for the calculation is presented first. Next, the results of a sample of simulations are presented, and finally some remarks on the comparison between qualitative and numerical models were made.

5.4.1 Methodology

To proceed with the comparison, three things are required:

a) the definition of equivalencies between qualitative and numerical values;

b) similar conditions for the simulations;

c) some criteria for drawing a conclusion about the comparison.

The methodology developed to fulfil these requirements starts with the definition of a set of correspondences between numerical and qualitative values for all of the quantities. Tables were created in which each qualitative value represented in the QS of the quantities was assigned to an interval of numerical values that the state variable, intermediate variables and parameters can take on.

The quantities plant (the state variable)[22], flower, seed , germ , establish and dead (the intermediate variables) had their QS associated with intervals between {1 - 100}, {1 - 1,000}, and {1 - 10,000}. These intervals start with one because the population never disappears in the qualitative model (section 5.3). Since simulations with these different intervals produced roughly the same results, only the {1-100} interval is shown here (Table 5.7). Note however that the final results of simulations may be greater than 100 and are equivalent to very many (ff).

quantitative range	**qualitative value**
1.00 - 19.99	very_few (pp)
20.00 - 39.99	few (p)
40.00 - 59.99	medium (m)
60.00 - 79.99	many (f)
> = 80.00	very_many (ff)

Table 5.7 Correspondences between numerical and qualitative values for the state variable and the intermediate variables.

Two different classes of parameters are included in the model. The first class includes the parameters representing soil water (soil) and temperature (temp). For these, numerical intervals between {0.10 - 0.90} were assigned arbitrarily to the qualitative values, as shown in Table 5. 8.

quantitative range	**qualitative values**
0.10 - 0.24	very_dry , very_cold (pp)
0.25 - 0.39	dry , cold (p)
0.40 - 0.54	medium , mild (m)
0.55 - 0.69	wet , hot (f)
0.70 - 0.90	very_wet , very_hot (ff)

Table 5.8 Correspondences for the parameters representing soil water and temperature.

[22]Note that the model has just one state variable, since 'population in the next time unit' refers to the same quantity plant in the next time step of the simulation.

The second class of parameters includes factors related to the production of flowers (typef) and seeds (types). In this case, each qualitative value was associated with a multiplication factor ranging from {1 - 3}, as illustrated in Table 5.9:

multiplication factor	**qualitative value**
1	small (m)
2	medium (f)
3	large (ff)

Table 5.9 Correspondences for parameters representing the number of flowers per plant and the number of seeds per flower.

Having defined correspondences between qualitative and quantitative values, simulations over just one time step were run with both models. This was done as a form of 'best case' analysis, because if the simulation runs over multiple time steps, the results obtained from the two models will diverge very much. The numerical values obtained with quantitative models easily become different from those obtained with the qualitative models implemented in this thesis. Beside that, the objective of this comparison is to calculate the values of the quantities during one state. Therefore we restrict ourselves to calculate the number of plants in the next time unit (nextpop) both as a number in *Life Cycle I*, the SD model, and as a qualitative value in *Life Cycle II*, the qualitative model.

Each simulation started with similar initial scenarios, defined by using the corresponding values for the initial number of plants (plant), number of flowers per plant (typef) and seeds per flower (types), soil water (soil) and temperature (temp).

Obviously there are several possible numerical values for each qualitative value. At least three values for the initial value of plant were tried: the minimum, median and maximum values of the interval. For example, if the initial number of plants was few (p), then the values 20, 30, and 39 (cf. Table 5.7) were used in simulations with the mathematical model.

Different values for the parameters were also tried. However, in order to reduce the number of tests, some values that were more likely to produce the best results were selected. For example, if soil was very dry (pp), the value 0.1 was used in the quantitative model; if it was medium (m) the values were 0.4 and 0.5. Two values were used here because the median of the interval is likely to be a turning point. If soil was very wet (ff), the quantitative model used 0.7 as input.

The results of the two simulations were compared by checking whether any numerical value of nextpop obtained in the SD model (*Life Cycle I*) was included in the interval associated with the qualitative value produced by the SIMAO model (*Life Cycle II*). There are two possibilities, either the number is included or it is not. If not, how big is the deviation? Is it acceptable? The following table (Table 5.10) shows the criteria used for the evaluation of the results (examples of how these criteria works are presented below):

Results of the simulation	**How big is the deviation?**	**Are the results similar?**
At least one numerical value obtained from the SD model is included in the interval associated with the qualitative value obtained by the SIMAO model.	There is no deviation between the outputs of both the quantitative and the qualitative models.	Yes, both models produced the same result. The same state of the system was predicted by both models (=*OK*).
None of the results obtained with numerical simulations is included in the interval associated with the qualitative values. The deviation has to be evaluated.	The magnitude of the deviation is smaller than 10% of the number generated by the quantitative model.	Yes, because the results produced by both models are very close (=*OK, very close*).
None of the results obtained with numerical simulations is included in the interval associated with the qualitative values. The deviation has to be evaluated.	The magnitude of the deviation is greater than 10% of the number generated by the quantitative model.	No, the two models produced different results from the same initial scenario (*diff. results*)

Table 5.10 Criteria used to compare the results obtained in the qualitative and quantitative models.

The criteria presented in Table 5.10 can be summarised as follows: there is a set of tables specifying correspondences between qualitative values and numerical intervals (Tables 5.7 - 5.9). Simulations start with similar initial scenarios. Each qualitative value for the number of plants was associated with three numerical values, covering the whole interval. The results from the two models were then compared. If at least one numerical value obtained from the quantitative model was included in the interval corresponding to the qualitative value obtained from the qualitative model, then the results were accepted as similar. There is a state of the system generated both by the quantitative and the qualitative models and no more tests are necessary.

If none of the numerical results fits within the interval associated with the qualitative result, then it is necessary to choose an acceptable limit for the deviation. For the purposes of this experiment, the limit was set intuitively at 10% of the numerical result. It is a flexible and still constant limit, because it changes with each result, and always corresponds to 10%. Therefore if the deviation is below 10% of the numerical result, then these results were considered similar results, because the results are very close. Above 10%, the results are considered different.

Table 5.11 shows a comparison between the results of the two models. It includes the qualitative (qual) and numerical (num) values for the inputs (plant, typef, types, soil, temp) and for the result of the simulation, the size of the population in the next time unit (nextpop). Table 5.11 also includes a conclusion about the similarity of the results.

plant qual/num		**typef qual/num**		**types qual/num**		**soil qual/num**		**temp qual/num**		**NextPop qual/num**		**Conclusion**
ff	80	m	1	m	1	pp	0.1	pp	0.1	f	73.37	OK
ff	80	m	1	m	1	m	0.4	m	0.4	f	84.27	OK very close
ff	80	f	2	f	2	m	0.4	m	0.4	f	111.49	diff. results

Table 5.11 Comparisons between simulations with qualitative and numerical models.

The scenario for the simulations represented in Table 5.11 can be described both in qualitative and in numerical terms. For example, the qualitative description of the scenario in the second row is: the number of plants in the population is very many (ff). They produce a small number of flowers per plant (m) and seeds per flower (m). Soil water is medium (m) and the temperature is mild (m). In this situation, the population in the next time unit decreases to many plants (f).

The numerical description of the scenario in the same row reads: there is a population with 80 plants producing 1 flower per plant and 1 seed per flower. Both soil water and temperature are represented by a multiplier equal to 0.4. In this situation the population in the next time unit consists of 84.27 plants.

The numerical interval corresponding to the qualitative result (f) is 60.00 - 79.99 (cf. Table 5.7). The numerical result of the simulation is 84.27. Given that 84.27 – 79.99 = 4.28 and this value is smaller than 10% of 84.27. Then the results were considered to be the same, because they are very close. Table 5.11 shows other scenarios to illustrate cases in which both models produce the same results (OK) and different results (diff. results).

5.4.2 Comparing the results of the two models

The following Table 5. 12 presents a sample of 45 simulations, showing the input and the results of the qualitative model *Life Cycle II*. The final column presents the conclusion about the comparison between the simulations in the qualitative and in the quantitative model *Life Cycle I*, using the methodology described in section 5.4.1. When the numerical result is not included in the interval associated with the qualitative value, the numerical result is presented between brackets beside the conclusion. It may be checked with the intervals associated to the qualitative values of nextpop in Table 5.12.

Plant	Typef	Types	Soil	Temp	nextpop	Conclusions about the results produced by the two models
pp	m	m	pp	pp	pp	OK
			m	m	p	OK
			ff	ff	p	OK
	f	f	pp	pp	pp	OK
			m	m	p	OK
			ff	ff	p	OK
	ff	ff	pp	pp	pp	OK
			m	m	p	OK
			ff	ff	p	OK
p	m	m	pp	pp	pp	OK
			m	m	m	OK
			ff	ff	m	OK
	f	f	pp	pp	pp	OK
			m	m	m	OK
			ff	ff	m	OK
	ff	ff	pp	pp	pp	OK
			m	m	m	OK
			ff	ff	m	diff. results (84.23)
m	m	m	pp	pp	p	OK
			m	m	f	OK
			ff	ff	f	OK
	f	f	pp	pp	p	OK
			m	m	f	OK
			ff	ff	f	diff. results (95.05)
	ff	ff	pp	pp	p	OK
			m	m	f	OK
			ff	ff	f	diff. results (165.37)
f	m	m	pp	pp	m	OK
			m	m	f	OK
			ff	ff	ff	OK
	f	f	pp	pp	m	OK
			m	m	ff	OK
			ff	ff	ff	OK
	ff	ff	pp	pp	m	OK
			m	m	ff	OK
			ff	ff	ff	OK
ff	m	m	pp	pp	f	OK
			m	m	f	OK very close (84.27)
			ff	ff	ff	OK
	f	f	pp	pp	f	OK
			m	m	f	diff. results (111.49)
			ff	ff	ff	OK
	ff	ff	pp	pp	f	OK
			m	m	f	diff. results (156.85)
			ff	ff	ff	OK

Table 5.12 Comparison between results obtained with the qualitative and the quantitative models.

The results presented in Table 5.12 can be summarised as follows. In this sample of 45 simulations, covering the whole range of values for the state variable and relevant combinations of parameters, the results are:

a) In 39 simulations the numerical value calculated from *Life Cycle I* (the SD model) is included in the interval that corresponds to the same qualitative value obtained from *Life Cycle II*(the SIMAO model). Thus both models generated the same results, from the same initial scenario.

b) In 1 simulation, the numerical result from *Life Cycle I* was 'very close' to the qualitative result from *Life Cycle II*, according to the criteria that the difference between both is smaller than 10% of the numerical result; thus both models produced the same results in this simulation too (cf. Table 5.12).

c) In 5 simulations the two models produced 'different results' starting with the same initial scenario. Since the differences were above the limit of 10%, it was concluded that the models did not derive the same predictions about the behaviour of the system. The numerical values obtained with the model *Life Cycle I* in these discrepant cases are presented between brackets, along with the qualitative values obtained with *Life Cycle II*. They can be compared by using the Table 5. 7.

5.4.3 Some comments about the comparison between the two models

a) Overall, it is fair to say that the qualitative model based in SIMAO produced the same results as those obtained from a SD model in simulations over one time step, starting with the same initial scenario, within the limits of the experiment described here. However, it is important to note that this is a superficial comparison. Appropriate statistical analysis should be used to support stronger claims about the similarities of the outputs of the two models.

b) The two models produced different results in only five simulations (out of 45). Three of the discrepancies between them happened in simulations starting with values p and m for the number of plants (plant), combined with elevated values of the four parameters (typef, types, soil, and temp), mostly ff or the equivalent values 3 and 0.7. The main reason for the discrepancy in these cases is the so called *continuity rule* (Chapter 4, section 4.3): it is assumed in qualitative modelling that a quantity cannot skip values on the quantity space. Therefore, if the initial value is p it can only increase to m (and from m to f), in spite of the value of growth rate. However, the two models predicted the same behaviour for the population: it was increasing in the three cases.

c) In the last two discrepant simulations opposite predictions of behaviour were reported. There, the initial value of the state variable was 80, the lowest value in the interval corresponding to ff, and the values of the parameters flower per plant and seeds per flower (2 and 3) were high. In these cases, and also in the only simulation with results 'very close' discussed above, the simulation with the quantitative model predicted increasing populations whereas the qualitative model showed decreasing populations.

d) Comparisons between different sets of observations or predictions about the same problem are quite common in ecological studies. For example, it happens when some empirical data are compared with the expected results produced by some statistical function. For the purposes of the present study, the *ad hoc* criteria defined to compare the results of the two models can be accepted. However, the development of methodologies for the evaluation of qualitative models, including the appropriate statistical analysis, is an important area for future researches.

The next section presents a third model of the same ecological problem described in section 5.1. The modelling formalism adopted is a combination of QPT and SIMAO.

5.5 Life Cycle III: introducing concepts and causal relations

As discussed in Chapter 4, QPT provides a convenient modelling language for representing the world as collections of objects whose properties are described in *views*, which in turn change under the influence of *processes*. A great deal of concepts students have to master about ecology fit into the notion of process well.

The direct influences introduced by processes set the derivatives of the quantities they influence. Qualitative proportionalities are used to represent the propagation of changes within the system. Through proportionalities, the derivative of a quantity sets the values of the derivatives of the quantities it influences. Direct influences and proportionalities thus represent the causal and the mathematical structures of the system being modelled.

However proportionalities do not carry much information about mathematical operations, and a formalisation of the qualitative calculus needed to implement qualitative equations within QPT has not been proposed so far. In qualitative models SIMAO is one possible approach to the implementation of details of the mathematical structure of the system. This section discusses how proportionalities can be translated into qualitative equations using SIMAO's algebra.

In the model *Life Cycle III*, the problem discussed in section 5.1 is conceptualised in terms of one process, *Population growth*, and two views, *Plant Population View* and *Environmental Conditions View*. These encode a representation for the conceptual and the causal structures of the system. Direct influences and proportionalities have a direct correspondence with the mathematical structure developed in the SIMAO model *Life Cycle II* (section 5.3). Consequently, in this process-oriented approach the same set of qualitative equations is used.

The results produced by this QPT-SIMAO model *Life Cycle III* are exactly the same as those produced by *Life Cycle II*, already discussed in the two previous sections. A different set of equations could have been used in Life Cycle III. However, this is not the point here. The reason for building this model is to explore its capacity for supporting explanation. This point will be discussed in Chapter 7.

5.5.1 Describing objects and situations

The system described in section 5.1 is represented in *Life Cycle III* as a plant population interacting with the cerrado. Accordingly, the library is organised around the objects plant , population and cerrado. Other related objects are flower, defined as part of plant, and seed, a stage of the development of plant. Finally, the cerrado has the component soil. The most interesting properties of these objects are modelled by the same quantities used in the model *Life Cycle II*, and are associated with the same quantity spaces (cf. Table 5.3).

Static knowledge about these objects, quantities and their relationship is captured in two model fragments, *Plant Population view* and *Environmental Conditions view*. The first is shown in Figure 5.3:

Plant Population View

Individuals

There is an object Population
There is a composite object Plant
Population consists of Plant
Plant has quantity number_of(Plant)
Plant has quantity number_of (Established_plant)
Plant has quantity number_of (Dead_plant)
Plant has quantity flowers per plant
Plant has quantity seeds per flower
.
There is an object Flower
Plant has part Flower
Plant has quantity number_of(Flower)

There is an object Seed
Plant has stage Seed
Plant has quantity number_of(Seed)
Plant has quantity number_of(Germinated_seed)

Preconditions

Environment favourable

Quantity Conditions

Am[number_of(Plant)] >= very_few

Relations

number_of(Flower) α_{Q+} number_of(Plant)
number_of(Flower) α_{Q+} flowers per plant
number_of(Seed) α_{Q+} number_of(Flower)
number_of(Seed) α_{Q+} seeds per flower
number_of(Germinated_seed) α_{Q+} number_of(Seed)
number_of (Established_plant), α_{Q+} number_of(Germinated_seed)
number_of (Established_plant), α_{Q-} number_of(Plant)
number_of (Dead_plant) α_{Q+} number_of(Plant)

Figure 5.3 *Plant Population View.*

The four parts of the *Plant Population View* can be read as follows: the system consists of a plant population, flowers, and seeds. The relevant quantities are the numbers of plants, flowers per plant, flowers, seeds per flower, seeds, germinated seeds, established and dead plants. A general statement about favourable environmental conditions[23] sets the external conditions for the view to be active. A restriction is placed on the quantity number of plants: it must be equal or greater than very_few . These conditions should be satisfied in the description of the initial

[23]This point would be expanded in future versions of this model.

scenario. Once active, the model fragment introduces a set of relations between the quantities, which are represented through proportionalities.

The second view in the library is the model fragment *Environmental Conditions View*. It represents knowledge about how the plant population interacts with the cerrado ecosystem (Figure 5.4):

Environmental conditions view

Individuals

There is an object Cerrado
There is an object Population
There is an object Plant
Cerrado has_population Population
Population consists of Plant
Plant has quantity number_of(Plant)
Plant has quantity number_of (Dead_plant)

There is an object Soil
Soil is part of Cerrado
Cerrado has quantity SoilWater
Cerrado has quantity Temperature

There is an object Seed
Plant has stage Seed
Plant has quantity number_of(Germinated_seed)

Preconditions

Environment favourable

Quantity Conditions

Am[number_of(Plant)] >= very_few
Am[number_of(Seed)] >= very_few
very wet >= SoilWater >= very dry
very hot >= Temperature >= very cold

Relations

number_of(Germinated_seed) α_{Q+} SoilWater
number_of(Germinated_seed) α_{Q+} Temperature
number_of (Dead_plant) α_{Q-} SoilWater

Figure 5.4 Environmental Conditions view.

The model fragment *Environmental Conditions View* (Figure 5.4) describes an ecosystem of cerrado, and one of its components, the soil, is the focus of attention. Soil properties considered here are temperature and humidity, modelled respectively by the quantities Temperature and SoilWater. The conditions for this model fragment to be active are: *Plant Population View* must be active, Temperature must have some value between very hot and very cold (for the cerrado standards), and SoilWater must have some value between very dry and very wet. These conditions are compared to the description of the initial state. When the model fragment is active, it introduces influences from the soil properties on germination and mortality of the plant population into the running model.

Proportionalities expressed in these views were implemented as qualitative equations with SIMAO's qualitative algebra (cf. Chapter 4, section 4.3), according to the following rules:

Qualitative proportionalities	**SIMAO's operators and laws**
positive proportionality	addition, multiplication, and the operator that increases the value of a quantity (incr)
negative proportionality	subtraction, the operators that decrease (decr) and invert (inv) the value of a quantity, and multiplication by the inverse

For example, the proportionality

number_of (*Established_plant*) α_{Q+} number_of(*Germinated_seed*)

can be read as follows:

> there is some mathematical function relating the number of established plants to the number of germinated seeds so that, if this is the only active influence, when the number of germinated seeds increases, so does the number of established plants.

If we have some information about the nature of the relationship, it is possible to give a more detailed account of the weak relations represented as indirect influences using SIMAO's algebra:

A[number_of (*Established_plant*)] =

number_of(*Germinated_seed*)] * inv(A[number_of(*Plant*)]

The same equation can also be implemented by using another QPT primitive, *correspondence*:

Correspondence((A[number_of (*Established_plant*)],
(A[number_of(*Germinated_seed*)] * inv(A[number_of(*Plant*)]))

5.5.2 A single process in the plant life cycle

Only one process, *Population Growth*, is considered in the model *Life Cycle III* (Figure 5.5). Also there is only one quantity directly influenced by this process, number of plants:

	Population growth process
Individuals	
	There is an object Cerrado There is an object Population There is an object Plant Cerrado has_population Population Population consists of Plant Plant has quantity number_of(Plant) Plant has quantity number_of (Established_plant) Plant has quantity number_of (Dead_plant)
Preconditions	
	Environment favourable
Quantity Conditions	
	Am[number_of(Plant)] >= very_few Active Plant Population view Active Environmental Conditions view
Relations	
	Plant has quantity Growth_rate Growth_rate α_{Q+} number_of(Established_plant) Growth_rate α_{Q-} number_of (Dead_plant) I+ (number_of(Plant) , Am[Growth_rate])

Figure 5.5 *Population growth* process

Process *Population growth* becomes active when the environment is favourable and both views *Plant Population* and *Environmental Conditions* are active. This process affects the plant population by changing the number of plants. The quantity that represents change is <u>growth rate</u>. In QPT derivatives of state variables are explicitly calculated by means of direct influence resolution (cf. Chapter 4). Since there is no other direct influence on the number of plants, its derivative will take the value of growth rate.

The proportionalities expressed in *Population growth* can the translated into the following equation:

Am[*growth_rate*] =

Am[number_of(*Established_plant*)] – Am[number_of (*Dead_plant*)]

However this expression cannot be used as it is to calculate growth rate, because SIMAO has no representation for zero and negative values. As in the model *Life Cycle II*(section 5.3), growth rate is not computed through any algebraic operation, but instead it is obtained by comparing the magnitudes of established and dead plants. This operation is described as follows:

a) if A[number_of (*Established_plant*)] > A[number_of(*Dead_plant*)] ,
then growth rate is positive and the number of plants will increase;

b) if A[number_of (*Established_plant*)] < A[number_of(*Dead_plant*)] ,
then growth rate is negative and the number of plants will decrease;

c) if A[number_of (*Established_plant*)] = A[number_of(*Dead_plant*)] ,
then growth rate is zero and the number of plants will remain the same.

As expected, simulations with the model obtained from this library produce exactly the same results as those obtained with the SIMAO-based model (Life Cycle II, section 5.3). These results were already presented in section 5.3, and compared with the output from an equivalent quantitative model in section 5.4. Explanations derived from this model will be presented in Chapter 7.

5.5.4 Some comments about Life Cycle III

a) The same problem modelled according to SD and SIMAO was represented, in much more detail, using QPT modelling primitives. The model *Life Cycle III* has a description of the conceptual structure of the system that includes objects, situations, processes and the conditions for things to happen. There is also a representation of the causal relations between the quantities. These elements will be used to build explanations, a point discussed in Chapter 7.

b) SIMAO's qualitative algebra can be used to implement more detailed representations for relations described in QPT models as proportionalities. The qualitative equations developed for the SIMAO- based model (section 5.3) were associated with the QPT modelling primitives without any extra requirements. As a consequence, the results obtained in simulations with this model are the same as those produced by the model *Life Cycle II*(section 5.3).

c) The QPT modelling language used in this model provides an explicit account of the feedback loop involving the number of plants. This quantity ultimately influences itself. As discussed in Chapter 4 (section 4.3), direct influences and proportionalities break the loop and explain how changes start and propagate causing the feedback.

d) There is still too much knowledge lumped together in *Life Cycle III*. Fire affects many aspects of the plant's life cycle, such as flower and seed production, germination, establishment and mortality. These elements are represented in this model as indirectly influenced quantities used to assess the effects of a single process, *Population Growth*. However, they are important ecological processes, and therefore they should be presented to the students in a learning environment.

In the next section a different representation for the problem discussed in section 5.1 is discussed, in which process *Population Growth* is disaggregated into the related processes of flowering, seed production, germination, establishment and mortality.

5.6 Life Cycle IV: process disaggregation

As commonly happens in modelling activities, it is possible to build alternative models of the same problem, exploring different aspects of the system. The model *Life Cycle III*, presented in the previous section, is based on a representation of how biological parameters and some environmental influences combine to affect one process, *Population Growth*, which in turn causes change in the number of plants in the population.

However, simulation based learning environments are more effective if there is a rich context for the student to explore. In QPT models this means having a large process vocabulary. The model presented in this section, *Life Cycle IV*, shows how the plant's life cycle can be described in terms of several processes, such as *Flowering, Seed_production, Germination, Establishment, Mortality and Population_growth*. Actually any of these processes can be disaggregated into others.

5.6.1 The library of Life Cycle IV

The model fragments from the library of the model *Life Cycle III* (that is, *Plant Population View*, *Environmental Conditions View* and *Population Growth* process) were used in this extended version. New model fragments were added to describe the possible situations in which plants can be found (such as flowered and dead plants), and the processes. The library of model *Life Cycle IV* has 12 model fragments altogether, shown in the Table 5.13a and b:

Views
Plant Population View
Environmental Conditions
Flowered Plant
Seed Plant
Seedling Plant
Dead Plant

Table 5.13a Library of *Life Cycle IV*- views.

Processes
Flowering
Seed Production
Germination
Establishment
Mortality
Population Growth

Table 5.13b Library of *Life Cycle IV*- processes.

Conditions for each process to occur are related to the availability of objects produced in another process. For instance, 'number of flowers greater than zero' is a condition for *Seed_production* to become active, and 'number of seeds greater than zero' a condition for *Germination* to be active. These and the *Flowering* processes involve physiological aspects that are not detailed in this model. Process *Establishment* in turn requires 'number of germinated seeds (seedlings) greater than zero'. Finally, process *Mortality* requires 'number of plants greater than zero'.

5.6.2 The mathematical structure revisited

In this model, a different representation of the influences on quantities was required, because those which were considered to be intermediate variables in *Life Cycle III* (number of flowers, number of seeds, number of germinated seeds, number of established plants, and number of dead plants) become state variables in the new version implemented in model *Life Cycle IV*. Thus they are directly influenced, and the constraints are placed on their derivatives, not on the quantities themselves.

As discussed in Chapter 4, (section 4.3), direct influences are combined by addition to determine the derivative of the influenced quantity. Often the actual values of these direct influences are not calculated, because QPT lacks an appropriate qualitative algebra. This is not the case here. In model *Life Cycle IV*, it is necessary to calculate the values of the rates of the processes, in order to update the value of each state variable. SIMAO's qualitative algebra was used in the same way as described in section 5.5, and the resulting qualitative equations are presented in Table 5.14:

Process	**Qualitative equation used to calculate the rate**
Flowering	A[Flowering_rate] = A[number_of(Plant)] * Typef
Seed_production	A[Seed_production_rate] = A[number_of(Flower)] * Types
Germination	A[Germination_rate] = A[number_of(Seed)] * Temperature * Soil)
Establishment	A[Establishment_rate]= $decr_1$ (A[number_of(Germinated_seed)] * inv(A[number_of(Plant)]
Mortality	A[Mortality_rate] = $decr_2$ (A[number_of(Plant)]) * inv(A[Soil]
Population_growth	Am[Growth_rate]= Am[number_of(Established_plant)] – Am[number_of (Dead_plant)]

Table 5.14: Qualitative equations used to calculate rates of the processes in model *Life Cycle IV*.

The values of the rates, calculated with the equations presented in the Table 5.14, are used to update the value of the state variable at each time unit. This can be done as follows:

a) given that in all these processes there is only one direct influence, which is positive, the value of the derivative of the state variable is equal to the value of the rate (Chapter 4, section 4.3);

b) next, the value of the derivative is added to the current value of the state variable, to produce the value of the state variable in the next time step;

c) it is assumed in this model that there are no flowers, seeds, germinated seeds and dead plants at the beginning of the simulation; also, it is assumed that the simulation runs over just one time unit;

d) consequently, the value of the state variable is equal to the value of its derivative, which is in turn equal to the rate of the process.

Consider the process *Flowering*, for example. It introduces the following direct influence:

I + (number_of(*Flower*), Am[*Flowering_rate*])

This relationship is represented by the qualitative equation

$$\text{Am}[\text{number\_of}(\textit{Flower})]_t = \text{Am}[\text{number\_of}(\textit{Flower})]_{t-1} + \text{Am}[\textit{Flowering\_rate}]$$

Assuming the value of Am[number_of(*Flower*)]$_{t-1}$ is zero, then this expression reads

$$\text{Am}[\text{number\_of}(\textit{Flower})] = \text{Am}[\textit{Flowering\_rate}]$$

and the value of <u>Flowering_rate</u> is calculated using the equation presented in Table 5.14. The same rationale is behind the calculation of the values of number of seeds, germinated seeds, established plants, and dead plants. So the mathematical structure of the system is ultimately very similar to those used in models *Life Cycle II* (section 5.3) and *Life Cycle III* (section 5.5).

Not surprisingly, the results obtained with the three models are the same, because they are based on very similar mathematical structures. The results were already presented in section 5.3 and compared to the results of the quantitative model in section 5.4.

5.6.3 Some comments about the model Life Cycle IV

a) Within the framework described in Chapter 4, this model has a more detailed representation of the conceptual structure of the system than the model *Life Cycle III* (section 5.5). Some processes can be aggregated or disaggregated and, as a result, the vocabulary encoded in the model is contracted or expanded, respectively. For educational purposes, this gives the modeller a great deal of flexibility, which can be used to explore different areas of the domain knowledge. Accordingly, explanations about a plant's life cycle can incorporate many accounts of ecological phenomena. This point will be explored in Chapter 7.

b) The causal structure in *Life Cycle IV* has more quantities directly influenced by processes. New quantities, the rates, were introduced to represent the dynamic aspects of the system. The mathematical structure used in the models *Life Cycle II* and *III* was modified to include the calculations for the rates of each process. The reinterpretation of the qualitative equations however did not alter the final results of the calculations. The results obtained with this multiple process-based model are the same as those obtained with the other two models, *Life Cycle II* and *III*.

c) The model *Life Cycle IV* produced the same results as the other qualitative models because it is based on very restrictive assumptions: a) the initial number of flowers, seeds, germinated seeds, established plants and dead plants are zero; b) the simulation runs over just one time step. As a consequence, it does not capture completely the dynamic aspects of the behaviour of the direct influenced quantities, as they are found in the real world. In the model, they are quantities whose value can change above and below their previous value. There is no representation in this model for things such as 'the number of flowers is decreasing', although it would be possible to implement one.

Life Cycle IV is a simple model, in which each state variable is influenced by only one process. More complex situations may pose different problems. In the next section, two of these potential problems are discussed: non-monotonic relationships between quantities and ambiguities in problem solving.

5.7 Non-monotonic relationships and ambiguity in qualitative models

In this section a model of one of the most important processes in the life cycle of cerrado plants is described: the establishment of very young individuals. This library introduces two new and important aspects of qualitative modelling.

Firstly, there is a need to handle non-monotonic relationships between quantities. Proportionalities were designed to represent monotonic relations (cf. Chapter 4). However, it is quite common to have quantities involved in complex relationships that are only monotonic within certain ranges of values. In this section a possible solution to this problem is presented. One model fragment is defined for each interval where the function relating the two quantities is monotonic. This way, we can represent a situation in which a particular quantity has a positive influence on another quantity within a certain range of values, and a negative influence in a different range of values.

Secondly, ambiguities are very likely to arise in simulations with qualitative models. This was not an issue in the previous models (sections 5.2 - 5.6) , in which the values were combined unambiguously. In this section how to handle the simulation when an ambiguity arises is discussed. There are basically three ways to deal with ambiguity:

a) ask the student to solve it;

b) use some additional annotation to describe the relationships that can be used to determine which are the most important influences;

c) explore all the possibilities, and report on all possible outcomes.

The first two options are explored here. It is discussed how the student can be called upon to solve ambiguities, and then an implementation of the model in which the causal dependencies (proportionalities) include knowledge about their strength is presented. The third possibility is the approach implemented in GARP (Bredeweg, 1992), the qualitative simulator used for building the models described in Chapter 6.

Initially, the main problems related to establishment are reviewed. This concentrates on Hoffmann's (1996) comparison of the behaviour of different species of cerrado plants under different environmental factors. Next a model *Establishment* is presented, by describing its views and processes. Finally, the behaviour of *Miconia albicans* is given as an example of how to handle non-monotonic relations and ambiguities.

5.7.1 Experimental data about establishment

As a general rule, seeds of cerrado plants germinate at the end of the dry season, or at the beginning of the wet season. It is a successful strategy because young plants (seedlings) are very sensitive to many factors such as water stress, high temperatures, and shortage of nutrients. These factors in turn are strongly related to the vegetation type. For example, these problems are more likely to occur in an open vegetation such as campo sujo or campo cerrado than in a forest type community such as cerradão. However, there's no universal behaviour among cerrado plants: some species are negatively affected by the established vegetation whereas other species are positively affected. These different responses can be observed after disturbances, such as fire events. For example, fire events are followed by increasing establishment and growth of seedlings in some species and decreasing in other species.

Hoffmann (1996) conducted some experiments to study the effects of fire and cover on the establishment of seedlings. Seeds from 12 species were sown under different environmental conditions to study the influences from time since last burning (0, 1, or 2 years, and the control >7 years) and density of cover (open, intermediate and dense) on the establishment success, that is, on the survival of seedling plants. He choose species of trees and shrubs exclusively to the cerradão, and species that can be found in other types of vegetation.

The results showed different rates of success under the experimental conditions. Cover had a positive overall effect on seedling establishment, a conclusion based on lower success in open sites. Species differed in response to cover: 9 species showed increased establishment in sites with woody cover and only one, *Miconia albicans*, showed negative effects from cover (establishment in open areas greater than in intermediate and dense areas).

Hoffmann also registered different effects from fire on establishment: it is significantly lower in recently burned areas (0 - 1 year). This negative immediate effect was found in all the 12 species, and disappeared after one year. Again *Miconia albicans* showed a very peculiar pattern of responses to fire, decreasing on the first year after fire, increasing very much on the second year, and decreasing again after two years. The peculiar behaviour of *Miconia albicans* can be related to the presence of a thick layer of litter: it has been observed in other studies that litter acts as a barrier to the establishment of seedlings in species with small seeds, such as *Miconia albicans*.

Hoffmann collected quantitative data on the behaviour of those 12 species and based his conclusions on statistical analysis. However there is also relevant knowledge expressed qualitatively in his work. For example, he describes the environment using terms such as <u>open</u>, <u>intermediate</u>, and <u>dense</u> for types of cover, and <u>dry</u> and <u>wet</u> for seasons. Also some of his results are presented in terms of <u>greater than</u>, <u>smaller than</u>. This is typical of research on the cerrado.

Experiments like those presented by Hoffmann provide the vocabulary for describing the quantities and how their qualitative values relate. The following model has been built using data collected by Hoffmann. It consists of a description of the objects, the main quantities involved and proportionalities used to calculate the establishment rate.

5.7.2 The Establishment model

The library of model fragments in *Establishment* is organised around the objects <u>plant</u>, <u>population</u> and <u>cerrado</u>. The relevant stages of development of <u>plant</u> are also considered to be objects: <u>germinated seed</u> and <u>seedling</u>. Other objects define various instances of plant species: <u>miconia</u>, <u>kielmeyera</u>, <u>guapira</u> and <u>brosimum</u>. These four species (*Miconia albicans*, *Kielmeyera coriacea*, *Guapira noxia*, and *Brosimum gaudichaudii*) are found in communities of campo sujo, campo cerrado and cerrado sensu stricto. *M. albicans* is a shrub, *K. coriacea* and *G. noxia* are trees and *B. gaudichaudii* can be found either as a shrub or a tree. They were selected because of their contrasting behaviour in reaction to the same environmental factors.

The properties considered in the model refer to the number of germinated seeds and established plants (seedlings), the amount of cover and the time elapsed since the last time unit. The quantities included in the model to express these properties are presented in Table 5.15:

Quantity	**Symbol**	**Quantity Space**
number of germinated seeds	GermSeed	{zero, plus}
number of seedlings	Seedling	{zero, plus }
establishment rate	EstabRate	{zero, plus}
amount of cover	Cover	{open,intermediate,dense}
time since last fire	LastFire	{0_ to_1,1_to_2, 2_to_3, >3, >=7}

Table 5.15 Quantities involved in calculations of establishment rate for four species of cerrado.

Two model fragments describe general views of the stages of the plant's development, *Germinated Seed* and *Seedling Plant*. They represent definitions that can combine with other model fragments to compose more detailed representations of the system. These model fragments are shown in Table 5.16.

	Germinated Seed View	**Seedling Plant View**
Individuals	There is object Plant There is object Germinated Seed Germinated Seed is a stage of development of Plant Germinated Seed has quantity number_of(GermSeed) Plant is a kind of Species	There is an object Plant There is an object Seedling Seedling is a stage of development of Plant Seedling has quantity number_of(Seedling) Plant is a kind of Species
Preconditions	Environment favourable	Environment favourable
Quantity Conditions	number_of(GermSeed) > zero	number_of(Seedling) > zero
Relations		

Table 5.16 Model fragments defining Germinated Seed and Seedling Plant in model *Establishment*.

Only one process, *Establishment*, is included in the model. It describes the relationships between the establishment rate, cover and time since the last fire. As mentioned above, these quantities are related by means of non-monotonic relationships, that vary according to the species being considered and the values of the influences themselves. In Figure 5.6 they are represented as proportionalities without signs:

	Establishment Process
Individuals	
	There is an object Cerrado There is an object Plant There is an object Germinated Seed There is an object Seedling Germinated Seed is a stage of development of Plant Seedling is a stage of development of Plant Plant is a kind of Species Cerrado has quantity Cover Cerrado has quantity LastFire Germinated Seed has quantity number_of(GermSeed) Seedling has quantity number_of(Seedling)
Preconditions	
	Environment favourable
Quantity Conditions	
	Active Germinated Seed View
Relations	
	There is quantity Establishment rate Establishment rate α_Q Cover Establishment rate α_Q LastFire correspondence(Establishment rate, (Cover, LastFire))
Influences	
	I– (number of (GermSeed), A[Establishment rate]) I+ (number of (Seedling), A[Establishment rate])

Figure 5.6 The *Establishment* process.

The relationships between establishment rate, cover and time since the last fire are described in the model fragment Process *Establishment* (Figure 5.6). These relationships are represented as proportionalities without signs, because the type of relation varies according to the species and the values of the influences themselves. This process has two effects: a negative direct influence on the number of germinated seeds, and a positive direct influence on the number of seedlings.

Different model fragments were included in the library specifying how the environmental influences affect the behaviour of each species. For example, Figure 5.7 specifies the effects of cover and fire on the establishment of *Miconia*, when there was a fire less than one year ago:

	Germinated Seed Miconia
Individuals	
	There is object Miconia Miconia is a type of Plant
Preconditions	
	LastFire < 1 year
Quantity Conditions	
	Active Germinated Seed View Active Establishment Process
Relations	
	Establishment rate α_{Q-} Cover Establishment rate α_{Q-} LastFire

Figure 5.7 Germinated Seed View of *Miconia* when the last fire occurred less the one year ago.

This model fragment (Figure 5.7) says that, if the last fire occurred less than one year ago, then in *M. albicans* the establishment is influenced negatively by cover. In other words, when cover increases, the rate of established plants decreases. It also says that the last fire has a negative influence on establishment rate, which decreases with time. The more time has passed since the event, the less its effect on establishment rate.

Model fragments with a similar configuration describe the behaviour of *M. albicans* under different conditions (Table 5.17):

Preconditions	Relations
1 year < LastFire < 2 years	Establishment rate α_{Q-} Cover Establishment rate α_{Q+} LastFire
LastFire > 2 years	Establishment rate α_{Q-} Cover

Table 5.17 Conditions and Relations in model fragments describing the behaviour of *M. albicans*.

According to the relations shown in Table 5.17, cover is always a negative influence for the establishment of *M. albicans*. For example, when cover moves from open to dense, the establishment rate decreases. In contrast, fire is a negative influence if the time since the last fire is less than one year, a positive influence during the interval between 1 and 2 years, and does not affect Establishment (and therefore is not represented in the model fragment) after two years.

It is very difficult to capture in mathematical equations complex behaviours such as that described for *M. albicans*. The same is true for qualitative equations. To implement the proportionalitites presented in Figures 5.6 and 5.7, a different approach was taken. A QPT modelling primitive, *correspondence*, is designed to combine particular values of the quantities (cf. Chapter 4, section 4.3). In this example, the values of establishment rate correspond to pairs of values of cover and time since the last fire, in accordance to Hoffmann's observations:

correspondence(Establishment rate, (Cover, LastFire))

For example, if cover is open and the time since the last fire is between one and two years, then the establishment rate of *M. albicans* takes the value positive.

5.7.4 Simulations with the Establishment model

The input for the simulation is given by the student, who enters the choice of species, and values for cover and the time since the last fire. A value is assigned to establishment rate in accordance to the condition specified in the input. Since this is the only direct influence on the number of established plants, the derivative of <u>number of (Seedling)</u> is equal to the value of establishment rate.

In situations involving so little information about the effects of the environmental factors on the quantities, ambiguity is very likely to arise. As mentioned in the introduction to section 5.7, two mechanisms for dealing with these situations were implemented: asking the student to solve the conflict, and adding information about their strength to the influences. The first approach will be now examined.

Suppose there is a population of *M. albicans* in an area where the vegetation is open, and there has been a fire event less than one year ago. The former is a positive influence, whereas the latter is a negative influence on establishment rate. Since there is no more information available, the simulation then stops and the student is asked which is the strongest influence. Figure 5.8 shows how the dialogue appears on the screen:

no more information available, the simulation then stops and the student is asked which is the strongest influence. Figure 5.8 shows how the dialogue appears on the screen:

```
What is the  species present ? (mic/kie/bro/gua)

>> mic.
How do you evaluate the cover on the ground ? (open/interm/dense)

>> open.
Time since last fire (years)? (zero/pp/p/m/f/ff)

>> zero.

Given that the species is Miconia,
and cover is small - open vegetation,
then influence from cover on establishment rate is positive;
the last fire was in the current season,
then influence from fire is negative.
Combined influences are ambiguous.

Given that there is an ambiguity, tell me:
which is the most important influence,
    1. cover, which is positive or
    2. fire, which is negative ?
(enter the number of your choice)

>> 1.

Then the establishment rate takes value positive
and the number of established plants increases.
```

Figure 5.8 Dialogue to solve ambiguity in a simulation with the model *Establishment*.

The second approach to dealing with ambiguities is to introduce some sort of annotation about the strength of the influences. This approach was suggested by D'Ambrosio (1987) and requires some reasoning about the nature of the proportionalities (positive or negative) and their current values. For example, consider the following situation: there is a quantity Q1 which is indirectly influenced positively by Q2 and negatively by Q3:

$$Q1 \;\; \alpha_{Q+} \;\; Q2$$

$$Q1 \;\; \alpha_{Q-} \;\; Q3$$

If the current values of their derivatives are D[Q2] < 0 and D[Q3] < 0, then there is an ambiguity: the first influence sets a negative value, and the second a positive value for the derivative of Q1. If the strength of both is known, then the strongest would determine the final result.

In the procedure implemented for doing influence resolution involving ambiguities, the proportionalities were re-written using a Prolog predicate with four arguments:

q_prop(InfluencingQ, InfluencedQ, Sign, Strength)

where <u>InfluencingQ</u> is the influencing quantity, <u>InfluencedQ</u> is the influenced quantity, <u>Sign</u> is the type of proportionality (positive or negative) and <u>Strength</u> is an annotation representing the strength of the influence. This last argument can take on the values {very_weak, weak, medium, strong, very_strong}. These values are associated with the symbols {pp, p, m, f, ff}, so that SIMAO's qualitative algebra can be used in calculations.

The first step in the influence resolution is to make lists of all the quantities that are indirect influences on the quantity in the current state. Two lists are produced according to the value of <u>Sign</u>, one with the positive influences and the other with the negative ones. Next the current values of the derivatives of these influencing quantities are used to update the actual impact each quantity will have on the derivative of the influenced quantity (<u>InfluencedQ</u>). Two new lists are produced, with influences that set positive and negative values.

Next the strength of these influences is compared. Since they are represented with SIMAO's algebra, it is possible to add the values of the strengths of all the negative influences and obtain a resultant strength. It is possible to say, for example, 'altogether, the negative influences have a weak effect on the quantity'.

The same is done with the positive influences, and a positive resultant strength is calculated. Finally, the two resultants are compared. If the sum of all the positive influences is stronger than the sum of all the negative influences, then the derivative of the influenced quantity will take the value positive. If the two resultants are equal, then the derivative is set to zero. Otherwise, it will be negative.

For example, assuming that the influence from cover is stronger than the influence from fire in the example given above (Figure 5.8), the derivative of establishment rate will be positive and the number of established plants will increase.

5.7.5 Some comments about the Establishment model

a) There is a great deal of flexibility in building qualitative models as libraries of model fragments. One example of such flexibility was given in this section: complex non-monotonic relations between quantities can be divided and described by model fragments representing ranges of values in which the function is monotonic.

b) Complex mathematical functions may be hard to capture, even in qualitative equations. In this case certain values of the quantities can be associated with the values of other quantities. In qualitative models, this kind of value correspondence can be implemented using the primitive *correspondence*.

c) Ambiguities are common in qualitative models. If properly explored they can be good opportunities for educational interactions,. The easiest way of solving ambiguities is to ask the user for a solution. This provides an opportunity for the students to exercise their capacity for judgement, or maybe to explore alternative hypotheses.

d) Ambiguities may also be solved by using information about the strength of an influence. However, as pointed out by D'Ambrosio (1987), annotations of strength that apply correctly to all situations are rare. It may happen that the strength of an influence is stronger under certain conditions than under different conditions. For example, the effects of fire on the vegetation are stronger in the dry season than in the wet season.

e) In the model direct influences and proportionalities are meant to have local effects. Incorporation of other quantities in more complex representations of the system may change the strength of relationships. For example, solar radiation influences the temperature at ground level. If however the soil is covered by vegetation, then the strength of the influence is reduced.

f) Given the points mentioned in items d and e above, annotations about the strength of influences applicable to the whole model should be avoided. They should be used carefully, in particular scenarios, states or to answer particular queries. They must be added to the QPT description of a scenario where necessary problem solving.

5.8 Conclusions

The four qualitative models described here provided a detailed account of what is happening to the system during one state of the simulation. A detailed representation of the mathematical structure of the ecological system and calculations of the values of the magnitudes of the quantities were used for determining state transitions, in simulations over one time step. In models designed to support simulations over multiple time steps, a detailed representation of the mathematical structure may be used, but it is not essential. The causal structure can provide the support for the simulation, and information about the derivatives of the quantities may be used to evaluate state transitions. This is the main point discussed in the next chapter.

Chapter 6 Simulations based on the causal structure

In the previous Chapter, simulation models with a detailed representation of the mathematical structure were described. State changes were predicted in terms of the magnitude of the quantities and the constraints between them. These models were used to make predictions about the system in the next time step, given the initial value of the magnitude of the state variable. A typical description of a simulation of this type is

> (s.6.1) 'Given that the population is small, produces few flowers, few seeds, germination is low and mortality is high, the population will become very small'.

However, a different approach to assessing state transitions during simulations is possible. Rather than dealing with the magnitude, this approach focus on the derivative of the quantities. In the framework proposed in Chapter 4 (section 4.2), this approach is based on the causal structure of the system. Simulation requires the initial value of the derivative of the state variable, described in the following statement:

> (s.6.2) 'Given that the population is decreasing (*and its magnitude is small*), the number of flowers may decrease. This, in turn, may cause the number of seeds to decrease. A decreasing number of seeds (*along with other influences*) may cause the number of germinated seeds to decrease, which may cause (*along with other influences*) the establishment to decrease. Given that mortality is increasing, then the population is likely to continue decreasing (*and its magnitude will become very small*)'.

Processes, assumed to be the only cause of change, introduce into the simulation values of derivatives of directly influenced quantities. These values of derivatives are propagated to other quantities through proportionalities, and are used to determine the values of the indirectly influenced quantities. Changes propagate until the initial quantity (number of plants in the above example) is influenced again. The direction of change remains the same. Consequently, according to the continuity rule, the magnitude moves to the next value on the QS (i.e. from small to very small).

There are many benefits from describing the dynamics of the system using the causal structure of the system. Firstly, this approach makes it explicit what is implicit in models built within SD (such as Life Cycle I, Chapter 5, section 5.2) and SIMAO (Life Cycle II, section 5.3). If we run a simulation over multiple time steps, both directly and indirectly influenced quantities will be changing. Assuming that we are interested in the behaviour of directly influenced quantities (cf. Chapter 4, section 4.1), the direction of change of intermediate quantities may be more relevant in describing the behaviour of the system than accounts of their magnitudes in each state. Secondly, a goal of QR is to build computer programs that draw useful conclusions about the physical world with little information. Calculations of magnitudes of all the quantities involved may be used to determine state transitions, but they are not essential for the qualitative modelling of dynamic systems.

It is worth noting that ambiguities are more likely to appear in simulations based on derivatives. In the statement above (s.6.2), the propagation of the effects was often conditional (*may cause* change). Derivatives can take on values in the QS = {–, 0, +}. In principle, when quantities with values + and – are combined, the result is ambiguous. What is then the role of ambiguity in qualitative simulation?

In the previous chapter (section 5.7) two mechanisms for solving ambiguities were implemented: asking the user for a solution and using annotations about the strength of the influences. In this chapter, a third approach is presented: when there is an ambiguity, the simulation carries on, exploring all the possibilities[24].

The models described in this chapter were developed in collaboration with Bert Bredeweg at the University of Amsterdam, and implemented in GARP (Bredeweg,

[24]The simulations described in this thesis are of the type *attainable envisionment*: given an initial scenario, they show all the possible behaviours of the system.

1992). The data structures used in GARP are presented in the Appendix. Part of this research was presented in Salles & Bredeweg (1997). We also used these models to explore the potential of qualitative models for explanation generation, in collaboration with Radboud Winkels at the University of Amsterdam. The results of those preliminary studies were reported in (Salles et al., 1997), and are discussed in Chapter 7.

The task was to build the library encoding the domain theory outlined in Chapter 4, Section 4.1, following the guidelines discussed in Section 4.5. The concept of population was recognised as the most important conceptual organiser for the domain. Relevant concepts included notions about what a population is, possible sizes, relevant behaviours and the effects of the processes natality, mortality, immigration, emigration. They were represented, as far as possible, according to the 'one concept, one model fragment' and the 'minimum required variation' rules.

GARP has the capacity to reason with a large number of model fragments. Therefore these models can represent more concepts about the domain. As discussed before, a well developed conceptual structure provides support for more detailed explanations (see Chapter 7).

The basic ontology adopted is QPT. The qualitative mathematics implemented in GARP is limited to the basic operations with signs, and reasoning with inequalities. Neither SIMAO nor any other approach was used, so the simulations were based mostly on the causal structure.

In section 6.1 the model fragments that constitute the kernel of the domain theory about population, as well as simulations starting with different initial scenarios are described. Next, the library is expanded to represent the influence of environmental factors on different types of populations. Section 6.2 describes some experiments representing alternative views of the same problem (germination). Depending on the purposes of the models, different QS for the same quantities, pruned by the 'minimum variation' rule (section 4.5) are used. The models described in sections 6.1 and 6.2 are 'running models' which explore the library of model fragments to create representations of one or two populations in the cerrado. In section 6.3 it is discussed how the library was expanded to include descriptions of the cerrado and of its communities, and the simulation of the effects of fire on succession in cerrado communities.

6.1 Building the kernel of a library of model fragments

Modelling in QR involves building libraries of model fragments. As discussed in Chapter 2, different running models are built by selecting subsets of model fragments in the library, hence the convenience of starting the library with a set of model fragments that can be assembled to run simple but basic models. Moreover, the library can be expanded around this core of model fragments in order to include other aspects of the domain knowledge.

In this section, the model fragments representing basic aspects of population dynamics are presented. They are the core of the library that has been built. As discussed in Chapter 4 (section 4.1), populations are groups of individuals that change because of natality, mortality, immigration and emigration. Therefore the model fragments presented here describe the population and these processes.

6.1.1 Objects

Objects are represented in a structured way, using the *isa* and *part_of* hierarchies. Therefore characteristics defined for objects at higher levels are inherited by objects at lower levels. The objects included in the library are represented in Figure 6.1:

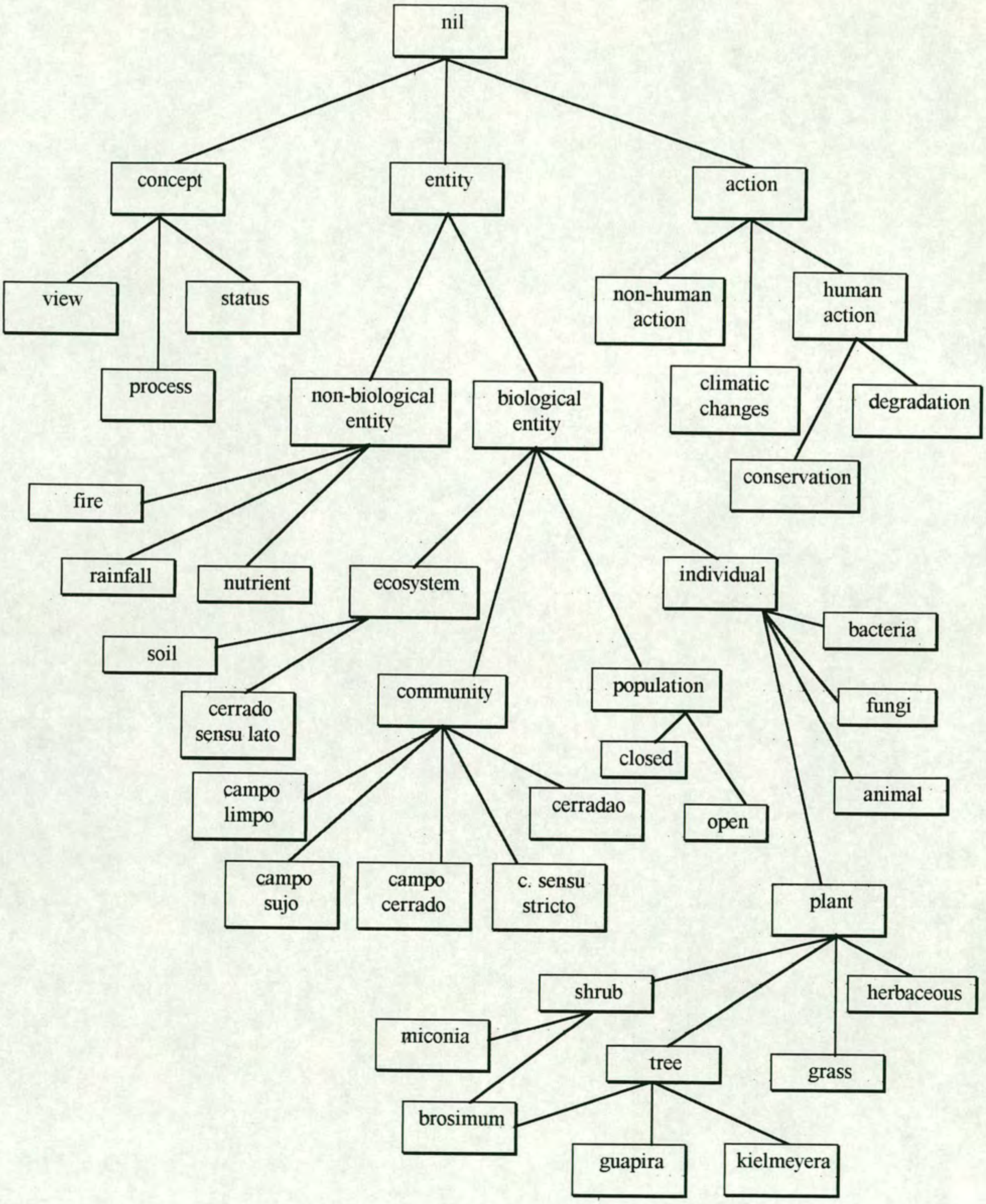

Figure 6.1 Hierarchy of objects.

For example, tree is a kind of plant, a kind of individual, which in turn is a biological entity. Kielmeyera is a type of tree, and therefore has the same attributes defined above. Note that an object can be related to more than one object at a higher level. For instance, Brosimum can be either a tree or a shrub.

It is possible to define relationships between objects in a model fragment. For example, to represent a population of *Kielmeyera coriacea*, consider the existence of the objects population and Kielmeyera, and add the information that population consists of Kielmeyera (details on how this is implemented in GARP are discussed in the Appendix).

6.1.2 Quantities and Quantity Spaces

The most important object in the domain theory implemented in this library is population. Accordingly, the most important quantity is Number_of, defined to represent the number of individuals in a population. The other quantities are related to the basic population processes: Born, Dead, Immigrated and Emigrated represent respectively the flows introduced by the processes *Natality*, *Mortality*, *Immigration* and *Emigration*. These flows introduce and remove individuals. Combined, they can be represented by the quantities Inflow and Outflow. A single process, *Population Growth*, represents an aggregation of the four basic processes. The unique flow introduced in this case is represented by the quantity Growth Rate. The Quantity Spaces associated with the magnitude of these quantities are shown in Table 6.1:

Quantity	**Quantity Spaces**
Number_of	{zero, low, medium, high, maximum}
Born, Dead, Immigrated, Emigrated, Inflow, Outflow	{zero, plus}
Growth Rate	{minus, zero, plus}

Table 6.1 Quantities and associated Quantity Spaces to describe populations.

These quantities can be instantiated to different objects. For example, it is possible to create models including populations of grass, shrub and trees. Each will have associated with all the quantities described in this Table (see examples in section 6.3).

It is worth noting that Inflow and Outflow cannot have negative values. Like in the Life Cycle series of qualitative models (see Chapter 5), GARP uses inequalities to determine whether the population should increase, remain steady or decrease. On the other hand, Growth Rate can take on a negative value (see section 6.1.4).

6.1.3 Views

As objects, model fragments can be represented in a structured way, using the *isa* and *part_of* hierarchies. Typically, general properties are defined at higher levels and inherited at lower levels. Relevant knowledge about existing populations was represented this way. There is a view describing *Existing Populations* and views describing direction of change (increasing, steady, decreasing), size (from zero or minimum, up to maximum), and type of organism (tree, shrub, grass, herbaceous). This hierarchy of model fragments is presented in Figure 6.2:

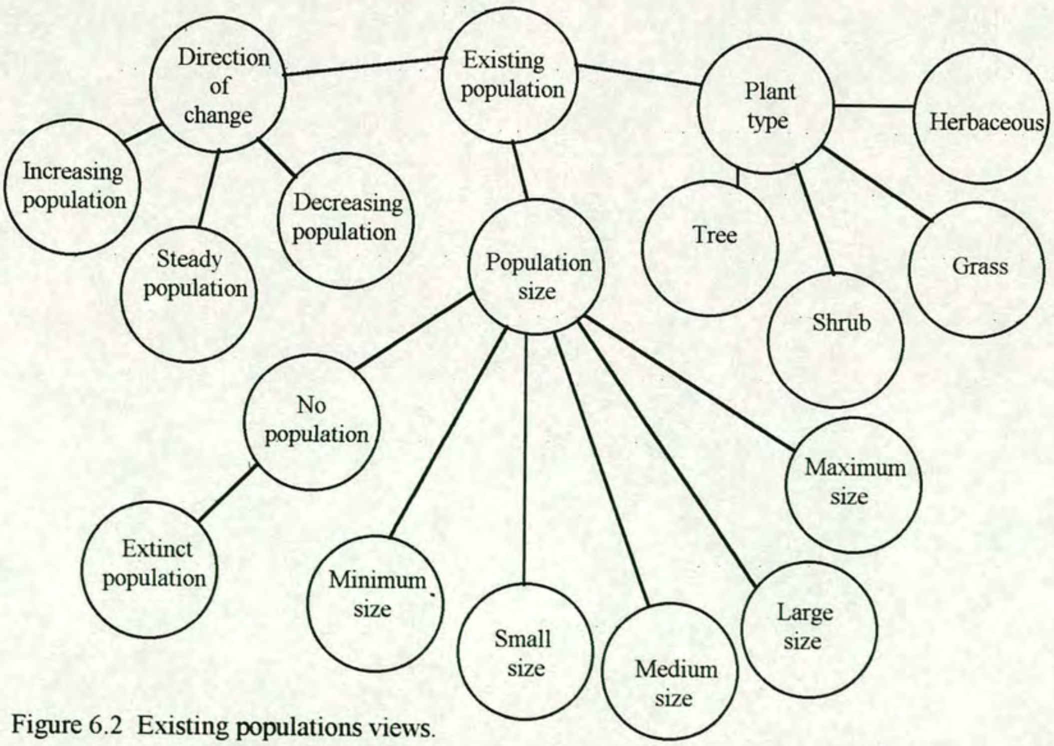

Figure 6.2 Existing populations views.

The absence of a population is modelled by a view called *No Population*. The condition for it to become active is that Number_of = zero. However, it may be interesting to represent a situation in which there has been a population, which decreased until disappear. This is captured in another fragment, called *Extinct Population*, defined as a type of *No Population*.

6.1.4 Processes

As discussed in Chapter 4 (section 4.1), changes may be caused either by one or more of the four basic processes (*Natality*, *Mortality*, *Emigration* and *Immigration*), or by an aggregated process combining these (*Population Growth*). In order to represent the variation observed in biological systems, these basic processes may include details relevant the behaviour of certain species. For example, *Colonisation* is a kind of immigration process, in which a population occupies an area previously empty (in this case, the active *No population* view is a condition for *Colonisation* to become active - see Chapter 4, section 4.3).

This knowledge can be captured by using the *isa* and *part_of* hierarchies to relate processes. Some examples are shown in Figure 6.3. The figure also shows composite processes and agent models, elements that will be discussed later (section 6.3).

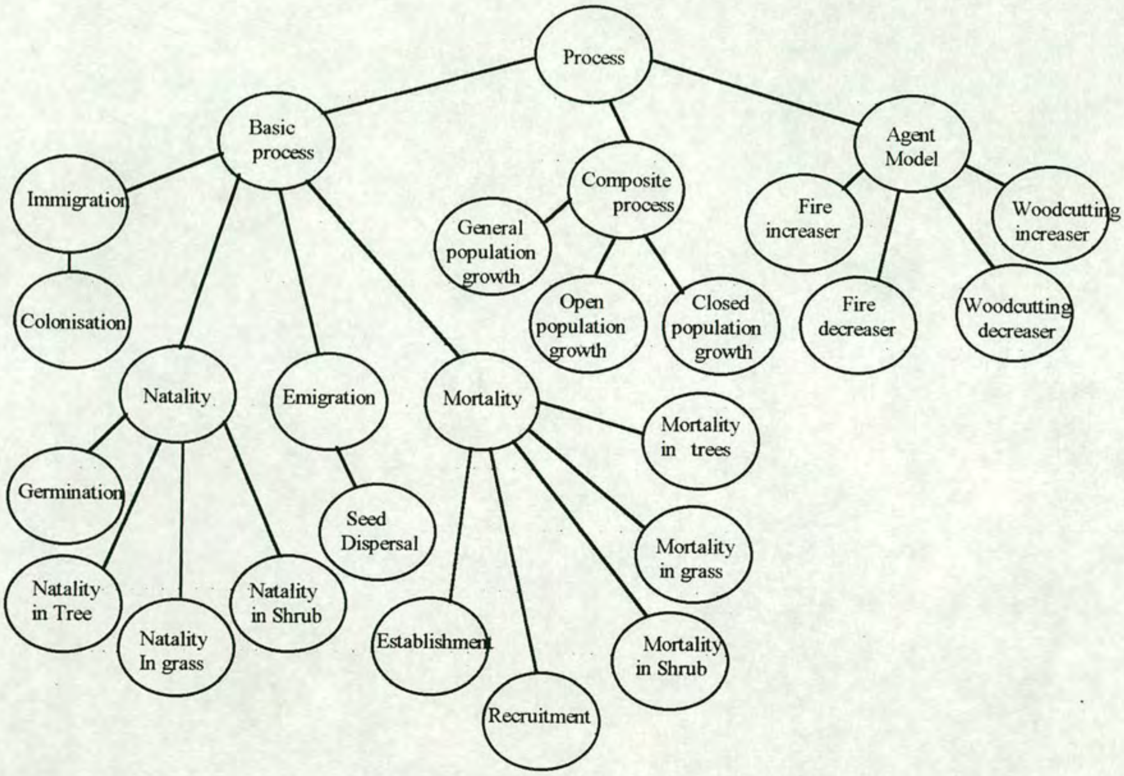

Figure 6.3 Hierarchy of processes.

Changes in the <u>Number of</u> can be modelled in at least two different ways:

1) by considering the four basic processes separately;

2) by aggregating them as a single process, *Population Growth*.

1) A more detailed representation of population change takes into account the four basic processes, modelled as four different flows, all of them affecting the same quantity, <u>Number_of</u>. The value for the derivative of <u>Number of</u> is defined by influence resolution.

In this case, similar flows can be combined into the quantities <u>Inflow</u>, representing individuals being born and individuals immigrating, and <u>Outflow</u>, representing individuals dying and emigrating. The derivative of <u>Number of</u> is calculated by comparing <u>Inflow</u> and <u>Outflow</u>:

$$\text{Am}[\mathit{Inflow}] = \text{Am}[\mathit{Born}] + \text{Am}[\mathit{Immigrated}] \qquad (1)$$

$$\text{Am}[\mathit{Outflow}] = \text{Am}[\mathit{Dead}] + \text{Am}[\mathit{Emigrated}] \qquad (2)$$

a) If Inflow > Outflow, then the derivative is positive and Number_of will increase;

b) If Inflow < Outflow, then the derivative is negative and Number_of will decrease;

c) If Inflow = Outflow, the derivative is zero and Number_of will not change;

This approach can be compared to the 'contained stuff' ontology used by Collins & Forbus (1989) to build models of thermodynamic processes. The idea is that there is an amount of 'stuff' being added to or subtracted from the 'contained stuff', while individuals are being added to or subtracted from the population. The quantity Number_of represents the 'amount of stuff' in the population.

2) Alternatively, we can consider only one process, called *Population Growth*, to be changing Number_of. In this case *Population Growth* is the aggregation of the basic processes, representing the numbers of individuals born, dead, immigrated and emigrated during that time interval. Given that this is the only process affecting this quantity, the derivative of Number_of takes the value of the flow introduced by this process, called Growth_rate (see Chapter 4, section 4.3).

One possible representation for *Population growth* uses the intermediate quantities Inflow and Outflow defined above to calculate the value of Growth_rate, the rate of *Population Growth*:

$$\text{Am}[\mathit{Growth\_rate}] = \text{Am}[\mathit{Inflow}] - \text{Am}[\mathit{Outflow}] \qquad (3)$$

The two representations are equivalent from the calculation point of view. However, in the latter case causality is hidden in the mathematical expression. In some situations, it can be more practical to use this representation. However, if we are interested in the details of the influences affecting the population growth, then a better option is to represent the four basic processes.

As presented above, *Population Growth* is a general process that expresses the behaviour of open populations. When representing populations in which there are no migratory movements (closed populations), *Population Growth* consists only of *Natality* and *Mortality*, and equation (3) is re-written as

$$\mathrm{Am}[\mathit{Growth\_rate}] = \mathrm{Am}[\mathit{Born}] - \mathrm{Am}[\mathit{Dead}] \qquad (4)$$

The model fragments described in the last two sections constitute the kernel of the library. They can be used to describe the most fundamental population behaviour. An example of a simulation is presented in the next section.

6.1.5 An example of simulation with the kernel of the library

The library, as described so far can be used to run simulations involving simple and basic facts about the population's behaviour. These can be very useful when discussing the forces driving changes in the population size. A wide variety of behaviours can be simulated, depending on the input from the initial scenario.

The initial scenario consists of specifications about objects, quantities, quantity values, and inequalities. It need not be detailed, provided the conditions for some views and processes to become active are met (see the Appendix). For example, the initial scenario describes the following situation: a plant population with size equal to low, and undefined (?) derivative. There are individuals being born, dying, immigrating and emigrating, at steady rates. The number of individuals being born is greater than those dying, and the number immigrating is smaller than those emigrating. This situation is summarised in Table 6.2:

Objects	population, plant
Values	Number_of = < low, ? > Born = < plus, zero > Dead = < plus, zero > Immigrated = < plus, zero > Emigrated = < plus, zero >
Relations	Born > Dead Immigrated < Emigrated

Table 6.2 An example of initial scenario for simulation.

The conditions defined above meet the requirements for the basic processes to become active. The derivative of Number of remains ambiguous, because there is no information with which to compare Born and Emigrated. There are three possibilities to be considered: either Born is greater than, equal to or smaller than Emigrated. Consequently, the derivative of Number of can be plus, zero or minus, respectively.

Accordingly, GARP produces three qualitative states corresponding to these situations, respectively states 1, 2 and 3 (Figure 6.4.)

```
number_of1(plant1)
[ ]  [ ]  [ ]  [ ]  [ ]  [0]  [ ]   maximum
| |  | |  | |  | |  | |  | |  | |
| |  | |  | |  | |  |+|  | |  | |   high
| |  | |  | |  | |  | |  | |  | |
[+]  [0]  [-]  [ ]  [ ]  [ ]  [ ]   medium
| |  | |  | |  | |  | |  | |  | |
| |  | |  | |  |-|  | |  | |  | |   low
| |  | |  | |  | |  | |  | |  | |
[ ]  [ ]  [ ]  [ ]  [ ]  [ ]  [0]   zero

1    2    3    4    5    6    7    state number
o-------------------->
          o---->
               o--------------->
                    o---->
```

Figure 6.4 The values of the magnitude (zero - maximum) and the derivative (−, 0, +) of the quantity Number_of, and the sequence of appearance of the seven states in a simulation[25].

The follow up from each of the three initial states is straightforward. With a positive derivative (state 1), the magnitude of the Number_of increases to high (state 5), and

[25]This Figure is a modified version of the output generated by GARP.

maximum (state 6). If the derivative is negative (state 3), the magnitude decreases to low (state 4) and zero (state 7). If the derivative is zero (state 2), the population size does not change.

6.2 Exploring Quantity Spaces

As discussed before (Chapter 4), in qualitative modelling only the most relevant values should be included in the QS of a quantity, and variation must be kept at the minimum level required by the purposes of the model. This section will show how different QS can be used to provide different perspectives on the same simulation.

6.2.1 Germination in cerrado plants

The ecological problem addressed here is the effects of fire on the germination of seeds in cerrado plants. Fire frequency is a component of the 'fire regime', and represents how often the cerrado is burned (Whelan, 1995). The overall frequency of fire in the cerrado is increasing, due to human actions (see Chapter 3). Fire frequency has some impact on many environmental factors. For example, it may affect the amount of woody plants (mainly trees) and indirectly influence cover (see Chapter 5, section 5.7) and illumination at the ground level. It is possible to say

(s.6.3) 'If fire frequency increases, cover decreases.'

(s.6.4) 'If fire frequency increases, the amount of light on the ground increases'.

It is accepted that, in general, trees and grass are differently affected by cover and light. This can be expressed as follows:

(s.6.5) 'If cover increases, germination in trees increases.'

(s.6.6) 'If cover increases, germination in grass decreases.'

(s.6.7) 'If light increases, germination in trees decreases.'

(s.6.8) 'If light increases, germination in grass increases.'

6.2.2 The knowledge representation

The notion of cerrado as an ecosystem is described in a single model fragment. It introduces the object cerrado, characterised by the quantities Fire frequency, Cover and Light. Human actions that affect fire frequency involve a series of complex processes for which a detailed account is not required here. GARP has a modelling primitive useful for these situations: *agent models* (Bredeweg, 1992). Agent models can be used to represent complex situations in which there are many different actions, affecting different quantities, but collectively acting in the same direction (see Appendix). In the present case, there is an agent model which represents actions that increase fire frequency (which could be called '*Degradation* process'). Another agent model represents actions that decrease fire frequency (which could be a '*Conservation* process'). Quantities affected by agent models are directly influenced quantities. Like other processes, agent models introduce a quantity that represents the rate of change, which sets the values of the derivatives of the quantities they influence. For example, when the agent model 'fire increaser' (*Degradation* process) is active, the derivative of Fire frequency is assigned a positive value equal to the value of the rate Fire increaser, and the quantity increases:

$$I+(\mathit{Fire\_frequency},\ A[\mathit{Fire\_increaser}])$$

The relations between Fire frequency, Cover and Light expressed in the statements (s.6.3) and (s.6.4) can be represented by the proportionalities as follows (Table 6.3):

English statement	Qualitative representation
(s.6.3)	Cover α_{Q-} Fire_frequency
(s.6.4)	Light α_{Q+} Fire_frequency

Table 6.3 Influences of fire frequency on cover and litter.

Other model fragments represent the objects tree and grass, defined as types of plant. It is assumed that *Germination* is a type of *Natality* process. In order to use the library described in the previous section, model fragments were used to define the effects of cover and light on the rate of individuals being born in populations of trees and grass. Accordingly, the proportionalities shown in Table 6.4 describe the behaviour of trees (see statements s.6.5 and s.6.7):

English statement	Qualitative representation
(s.6.5)	*Born* α_{Q+} *Cover*
(s.6.7)	*Born* α_{Q-} *Light*

Table 6.4 Influences from cover and light on the 'born' flow of trees.

For grass, influences of Cover and Light on *Natality* are represented in Table 6.5:

English statement	Qualitative representation
(s.6.6)	*Born* α_{Q-} *Cover*
(s.6.8)	*Born* α_{Q+} *Light*

Table 6.5 Influences from cover and light on the 'born' flow of grass.

6.2.3 The simulations

Simulations start with an initial scenario including the initial values of the quantities and the conditions for one of the agent models to become active. Since the focus is on the causal structure, simulations could be described as follows:

(s.6.9) 'If human actions cause fire frequency to increase, then cover will decrease and the amount of light on the ground will increase. Consequently, the number of germinated tree seeds will decrease and germinated grass seeds will increase.'

The objective of these simulations was to explore the use of alternative QS for creating different perspectives of the same problem. In different simulations, two sets of possible values were assigned to the magnitudes of quantities:

{ zero, plus}

{ zero, low, medium, high, maximum}

For example, <u>Cover</u> can be the only quantity with the bigger QS, while all the other quantities have the smallest. A simulation in a scenario of decreasing fire frequency may be described by the following statement:

(s.6.10) 'If human actions cause fire frequency to decrease to <u>zero</u>, then cover will increase to <u>maximum</u> and the amount of light in the ground will decrease to <u>zero</u>. Consequently, the number of germinated trees seeds will increase to <u>plus</u> and germinated grass seeds will decrease to <u>zero</u>.'

6.2.4 Some comments

In qualitative models, the use of alternative QS's allows great flexibility in representing different views of the system's behaviour. It is not difficult to imagine how the statement (s.6.10) could be rewritten to express simulations focused on quantities other than <u>Cover</u>. Note also that, although full of references to the magnitude of the quantities, the statement (s.6.10) describes a simulation based on the causal structure, in which the values of the magnitudes are not obtained by actual calculations. In conclusion, the causal structure provides a framework for generating statements such as (s.6.9), which can be filled in with the magnitudes of the quantities during the simulation resulting in statements such as (s.6.10).

Alternative QS can be used to focus on certain quantities, according to the purposes of the model, generating different explanations for the same problem. This approach can potentially widen the range of explanations provided in a learning environment (see Chapter 7).

The library of model fragments was further expanded with a more detailed representation of the cerrado ecosystem, including other environmental factors. This is described in the next section.

6.3 Scaling up the size of the library

It was shown in the previous sections that there are many factors to consider when expanding the library. As a rule, if the number of quantities involved in the simulation increases, there will be more possible values and relations to be considered, more alternative scenarios to be examined, and more computational resources will be used. Ambiguity is possibly the most critical factor in scaling up the size of the library. Its effect on the simulation is exponential, and can easily make the envisionment graph intractable. This section describes how the library was augmented to represent more detailed knowledge about the effects of fire on the cerrado, while keeping the simulation under control.

6.3.1 Succession in cerrado communities

The overall influence of fire frequency on the structure of the cerrado vegetation can be expressed as follows:

> (s.6.11) 'If fire frequency decreases, then the vegetation will become more dense, with more trees and shrubs and less grass.'

> (s.6.12) 'If fire frequency increases, then the vegetation will become more open, with less trees and shrubs and more grass.'

These hypotheses are supported by long term studies in protected areas, and are widely accepted by Brazilian researchers, teachers and management workers. They have been expressed in one form or another in the literature (for example, Coutinho, 1990; Pivello, 1992; Pivello & Coutinho, 1995; Moreira, 1992), and in the interviews with Brazilian researchers and teachers (see Chapter 3).

Communities are groups of populations of all species living in a certain area during a period of time. Cerrado communities can be classified according to the quantities of trees, shrubs, herbaceous plants and graminoid plants. Typically different proportions of these plants make physiognomies such as campo limpo, campo sujo, campo cerrado, cerrado sensu stricto and cerradão (see Chapter 3).

From statements (s.6.11) and (s.6.12), it can be inferred that, in ideal conditions, a protected vegetation may become cerradão. Alternatively, only campo limpo can stabilise under high frequencies of burning.

This behaviour of the vegetation can be explained in terms of the effects of fire and other environmental factors on the dynamic aspects of the populations. As mentioned before (Chapter 5, section 5.1), flowering, germination and establishment are sensitive stages in the life cycle of cerrado plants.

Fire frequency influences the vegetation as a whole, and consequently, influences the canopy of the trees (cover) and the material that covers the ground (litter). The influence from fire frequency on cover has already been described in the statement (s.6.3). However, unlike the implementation presented in section 6.1.6, cover here has a value corresponding to the number of trees. Cover is also an influence on litter, described as follows:

(s.6.13) 'If cover increases, litter increases.'

Litter is a general term designating the dead material such as leaves, flowers, fruits, and small pieces of wood that accumulate on the ground. Not only the quantity but also the composition of the litter changes according to the community type. For example, cerradão (a forest-like community) has more litter than the campo sujo (a grassland-like community). Also, pieces of woody material and the components of the litter are bigger in the cerradão. It is accepted that

(s.6.14) 'If fire frequency increases, the amount of litter decreases.'

Litter creates a micro-environment at the ground level, with particular conditions of light, temperature, humidity and nutrient availability. It has great ecological importance, because is the environment where plants germinate and establish.

In general, litter can be associated with these environmental factors as follows:

(s.6.15) 'If litter increases, the humidity at the ground level increases.'

(s.6.16) 'If litter increases, the amount of available nutrient increases.'

(s.6.17) 'If litter increases, the temperature decreases.'

(s.6.18) 'If litter increases, the amount of light decreases.'

These factors influence populations of trees, shrubs, herbaceous and grass plants differently. It was anticipated in the previous section that these types of plants can be organised into three functional groups (trees, shrubs and grass). Some factors such as humidity and nutrient availability have the same influence on all three groups:

(s.6.19) 'If humidity increases, germination in trees, shrubs and grass increases.'

(s.6.20) 'If nutrient availability increases, germination in trees, shrubs and grass increases.'

(s.6.21) 'If humidity increases, mortality in trees, shrubs and grass decreases.'

(s.6.22) 'If nutrient availability increases, mortality in trees, shrubs and grass decreases.'

Temperature and light account for different behaviour in trees, shrubs and grass. We assume here that these factors affect trees and shrubs in the same way, whereas grass behaves differently. The effects of light on trees (and shrubs) and grass were already mentioned (s.6.7 and s.6.8). The influence from temperature at the ground level can be described as follows:

(s.6.23) 'If temperature increases, germination in trees and shrubs decreases.'

(s.6.24) 'If temperature increases, germination in grass increases.'

(s.6.25) 'If temperature increases, mortality in trees and shrubs increases.'

(s.6.26) 'If temperature increases, mortality in grass decreases.'

6.3.2 The knowledge representation

The knowledge expressed above can be formalised as follows. The cerrado ecosystem was described at a higher level in the *Cerrado Sensu Lato view*. Using the *isa* hierarchy implemented in GARP, a set of model fragments represents the cerrado communities. In addition to the main communities described in Chapter 3, some intermediate types were included in order to make the transitions clearer (Figure 6.5):

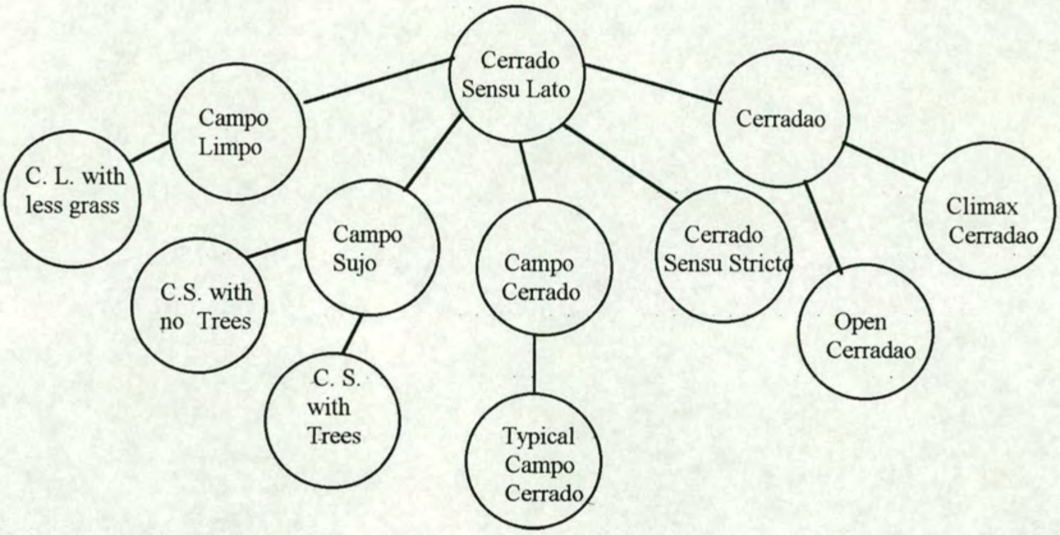

Figure 6.5. Model fragments about communities.

The *Cerrado Sensu Lato* view and its instances include the objects cerrado, population, tree, shrub, and grass. The object cerrado is defined as consisting of population(s) of tree, shrub, and grass. The number of individuals in each population can take on values {zero, low, medium, high, maximum}, as described in the core model fragments of the library (section 6.1).

On the basis of the values of trees, shrubs and grass, it is possible to characterise the cerrado communities. The combinations implemented in each model fragment are expressed in Table 6.6:

Community	Grass	Shrubs	Trees
campo limpo less grass	< maximum	= zero	= zero
campo limpo	> medium	= zero	= zero
campo sujo no trees	= high	= low	= zero
campo sujo with trees	= high	= low	< medium
campo cerrado	> zero & < maximum	> zero & < maximum	= medium
typical campo cerrado	= medium	= medium	= medium
cerrado sensu stricto	= low	>= medium	= high
open cerradão	= zero	= high	> medium
cerradão	= zero	= high	= maximum

Table 6.6 Values for trees, shrubs and grass defining the cerrado communities.

The object <u>cerrado</u> is also associated with some environmental factors. The quantities that describe these properties of the <u>cerrado</u> and their QS are shown in Table 6.7:

Quantity	Quantity Space
Fire frequency	{zero, plus}
Litter, Humidity, Light, Nutrient, Temperature	{plus}
Cover	{zero, low, medium, high, maximum}

Table 6.7 Quantities related to the object <u>cerrado</u> to represent environmental factors.

The object <u>cerrado</u> is also associated to fire frequency, litter, humidity, light, nutrient and temperature.

The influence of <u>Fire</u> <u>frequency</u> on the community is indirect: it propagates through a network of indirect influences among environmental factors. It is assumed that these environmental factors are always present in any scenario described by the models. Hence their QS is {plus}.

<u>Fire</u> <u>frequency</u> influences <u>Cover</u> (shade produced by the canopy of the trees), and this is an important influence on all the other factors. The number of trees is also an indirect influence on <u>Cover</u>, and therefore it was modelled as a positive proportionality:

$$\text{Cover} \ \ \alpha_{Q+} \ \text{Number of (Tree)}$$

However more information can be added to this relation. It is assumed that there is a direct correspondence between the number of trees and cover. For example, when the number of trees is low, so is cover. This relationship was implemented by using a GARP primitive called *direct quantity space correspondence*. This way, any value assigned tree is also assigned to cover (see Chapter 4, section 4.3 and the Appendix).

The relationships between the quantities that represent environmental factors, outlined in the previous section, are shown in the Table 6.8:

English statement	**Qualitative representation**
(s.6.3)	Cover α_{Q-} Fire frequency
(s.6.13)	Litter α_{Q+} Cover
(s.6.14)	Litter α_{Q-} Fire frequency
(s.6.15)	Humidity α_{Q+} Litter
(s.6.16)	Nutrient α_{Q+} Litter
(s.6.17)	Temperature α_{Q-} Litter
(s.6.18)	Light α_{Q-} Litter

Table 6.8 Qualitative representations of the relations between environmental factors.

The effects of environmental factors on population parameters are simulated via the rates of the basic processes. As mentioned in the previous section, different species react differently to environmental factors. More details representing specifications of the *Natality* and *Mortality* processes were introduced to model fragments: *Natality in trees*, *Natality in shrub*, *Natality in grass*, *Mortality in tree*, *Mortality in shrub* and *Mortality in grass*. The most relevant features of these processes are discussed next.

<u>Humidity</u> and the <u>Nutrients</u> influence *Natality* and *Mortality* in trees, shrubs and grass in the same way, as shown in Table 6.9

English statement	Qualitative representation
(s.6.19)	Born α_{Q+} Humidity
(s.6.20)	Born α_{Q+} Nutrient
(s.6.21)	Dead α_{Q-} Humidity
(s.6.22)	Dead α_{Q-} Nutrient

Table 6.9 Influences of humidity and nutrient availability on trees, shrubs and grass.

The effects of the temperature on *Natality* and *Mortality* of trees and shrubs are represented in Table 6.10:

English statement	Qualitative representation
(s.6.23)	Born α_{Q-} Temperature
(s.6.25)	Dead α_{Q+} Temperature

Table 6.10 Influence of temperature on trees and shrubs.

The influence of temperature on *Natality* and *Mortality* in grass is described in Table 6.11:

English statement	Qualitative representation
(s.6.24)	Born α_{Q+} Temperature
(s.6.26)	Dead α_{Q-} Temperature

Table 6.11 Influence of temperature on grass.

Finally, the four basic processes affect the number of trees and shrubs. The full causal structure of the system is represented by 16 direct influences and 32 indirect influences, affecting 33 quantities. It is shown in Figure 6.6:

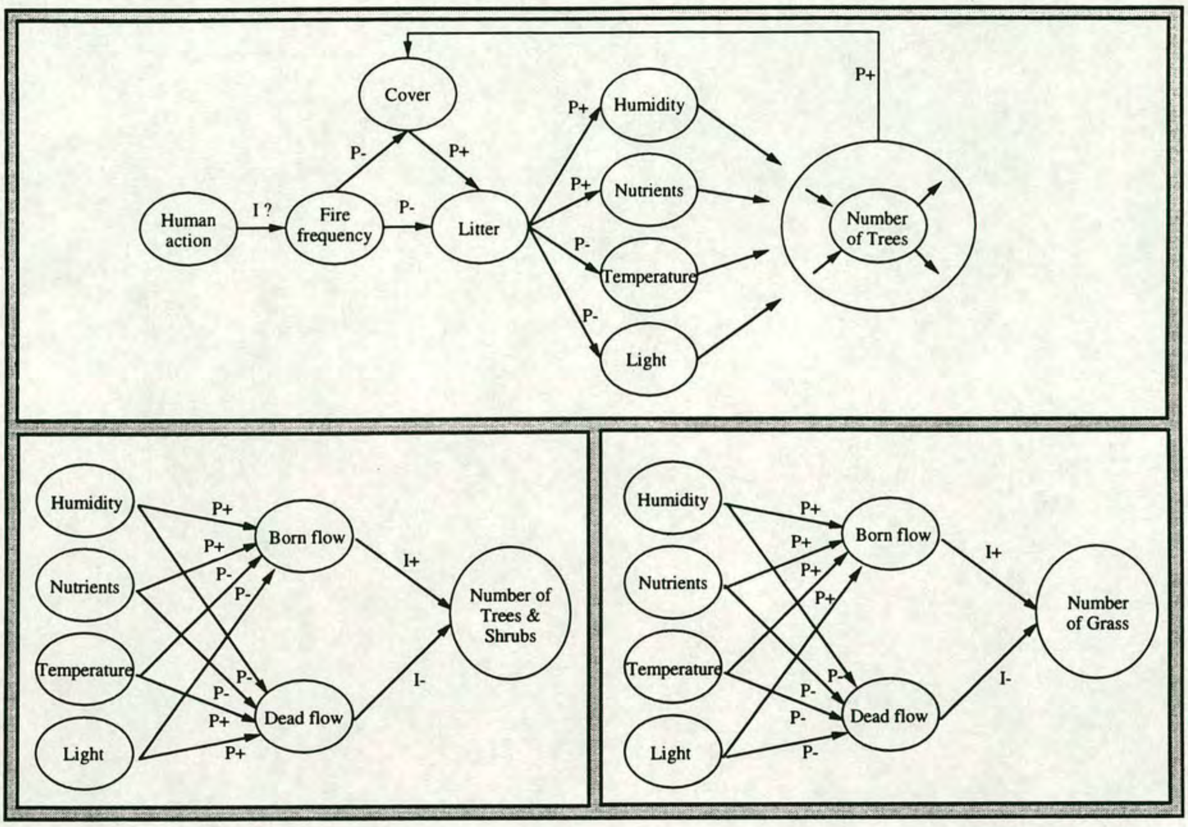

Figure 6.6. The diagrammatic representation of the causal structure.

This causal structure can be used partially or in full, to support simulations showing different aspects of the cerrado. This will be discussed in the next section.

6.3.3 Simulations

Using different initial scenarios, the library can be used to run several simulations showing different behaviours. Initially simulations with the part of library referring to the communities excluding the environmental factors were run. In GARP, if the initial scenario does not introduce the environmental factors, they are not taken into account. In this case, the simulation shows the possible changes in the community in a much less constrained way. As a result the envisionment graph shows a large number of possible states ranging from 'cerradão' to 'campo limpo less grass', all of them identified as one of the cerrado communities mentioned above (Table 6.3). This result was expected, given the loose definitions of the communities (see, for example, the definition of the campo cerrado community).

For example, in one simulation starting with a community of campo limpo with fire frequency decreasing, the community evolved to become a cerradão, producing a graph with 25 states including all the intermediate communities. Another simulation, starting with cerradão with fire frequency increasing, produced 26 states until campo limpo was reached. Finally, a simulation starting with a typical campo cerrado (number of trees, shrubs and grass equal to medium), and leaving the initial values of the flows of the basic processes undefined, resulted in a graph consisting of 84 states, and ending in the two extremes of communities ('campo limpo less grass' and 'cerradão').

However, such a large number of states is hardly interesting in an educational interaction. When the environmental factors were introduced, the number of ambiguities increased significantly, leading to a large number of possible states. In order to control the simulation, some assumptions were added to the model. The most important are:

a) the campo cerrado community was redefined as a typical community with the values for trees, shrubs and grass equal to medium. The effect of this assumption can be seen in the graph: there is some branching from the campo limpo and campo sujo, but after the typical campo cerrado community was reached, the simulation moved without branching up to cerradão.

b) the influences from *Humidity* and *Nutrient* on the population of grass were removed to reduce ambiguities. They do not give an account for different behaviours of grass and trees/shrubs. The running models therefore kept the most relevant knowledge about the influence of environmental factors.

c) Finally, some termination rules (see Appendix) were introduced in order to avoid terminations that are very unlikely to happen. For example, we assume that *Natality* will be active as long as there is a population. However, <u>Born</u> may decrease due to influences from environmental factors, and its value may go to zero. So we added a termination rule with the assumption that this can only happen when the population becomes extinct. Assumptions such as this one speed up the simulation and make the results clearer and easier to understand.

When these restrictions were introduced into the simulation, the number of states decreased significantly. As a result, a full simulation with the model presented in this section, starting with a campo limpo and fire decreasing, produced the envisionment graph with 13 states, presented in Figure 6.7.

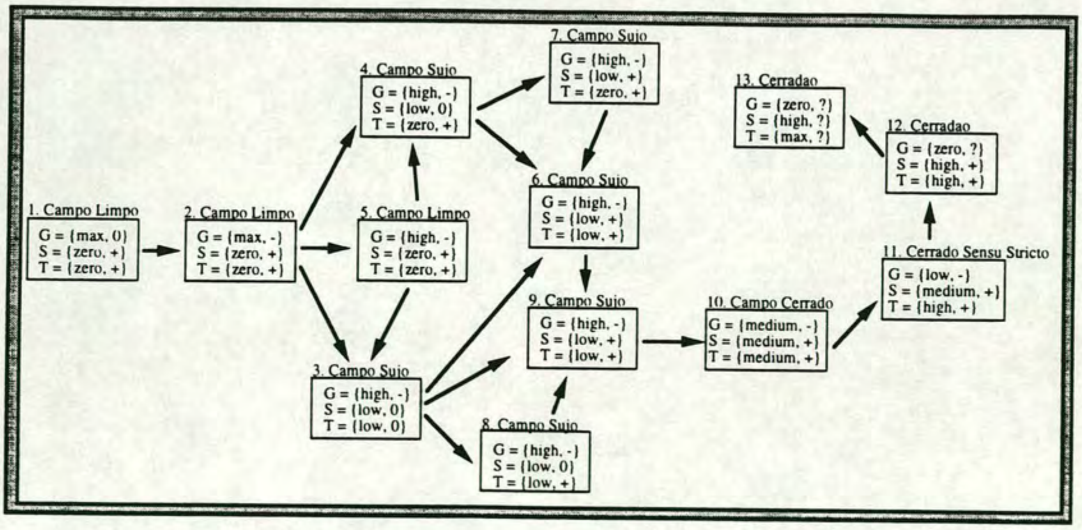

Figure 6.7. The envisionment graph for succession.

This envisionment graph shows the succession changes in the cerrado as predicted by the hypotheses stated in the beginning of this section. The use of this simulation for educational purposes is discussed in Chapter 7.

6.3.4 Some comments

There are three components to consider in simulations using qualitative models: the initial scenarios, the set of views and processes, and the envisionment graph. The first are partial descriptions of the system, and constitute 'entrance doors' for the library. The second is the main part of the library, and encodes the domain knowledge. The third is the output of the combination of the previous two components, and describes the behaviour of the system.

The library is built incrementally, starting with a kernel of model fragments that can be used later to compose more complex running models of the domain. It was noticed that, in the beginning, it is necessary to implement a relatively large number of model fragments in order to obtain a relatively small number of running models. However, once the kernel of the library is developed, a relatively small number of new model fragments allow for a relatively large number of new running models. This point can be exemplified by using the kernel of the library covering population dynamics (section 6.1) to describe the behaviour of the cerrado communities (section 6.3).

How good is the representation of the domain knowledge encoded in the library? An informal measure of the quality of the library can be obtained by comparing the number of initial scenarios (and therefore the number of possible running models) and the size of the library (taken by the number of model fragments). It is proposed that the ratio 'number of initial scenarios / number of model fragments in the library' can be used to evaluate the quality of the representation. High values for this ratio are an indication that the library encodes general aspects of the domain. The modeller was probably successful in searching for the basic organising principles (Chapter 4, section 4.5), and consequently a small set of model fragments can be combined to compose many different scenarios. If, on the contrary, the values of this ratio are low, then the library is more specific. A large number of model fragments are being used to describe few scenarios. For example, the kernel of the library described in section 6.1 can be associated with a large number of initial scenarios. In contrast, the representation of germination in section 6.2 (apart from using different QS for the quantities) is more restricted and allows for more specific simulations.

Ambiguity can be interesting because it allows representations of different possible behaviours of the system. However, it can cause the simulation to explode into a large number of states. The modeller can keep the simulation under control by using different approaches. Some were used in this chapter: restrict the QS, make simplifying assumptions, or create specific rules for eliminating terminations with low probability of occurrence.

In conclusion, it is possible to define the 'ideal' library as a library with a small number of model fragments, that accepts a large number of initial scenarios and produces a large number of running models. The 'ideal' library can be expanded with few new model fragments to produce more running models. This library also encodes knowledge that controls ambiguities and keeps the simulation within manageable limits. These observations may be useful for others interested in developing qualitative models.

6.4 Conclusions

The library described in this chapter shows that the causal structure can support simulations and reasoning about the magnitude of the quantities. Calculations of the values of the quantities by means of detailed accounts of the mathematical structure are not essential. Similar results can be obtained by propagating the influences and changing values according to the continuity rule.

The correct selection of basic concepts is of fundamental importance for the success of the modelling task. The library is developed around a core of model fragments representing these basic concepts. They should be general enough to be incorporated into more complex representations of the domain knowledge.

Different QS can be associated with the same quantity to achieve different educational goals. It was shown that different QS for the same set of quantities can be used to create alternative representations of the same scenario. This approach can be used to focus on different aspects of the system being modelled, and thus to create alternative vocabularies for the explanatory discourse.

Ambiguities are more likely to arise with a loose representation of the quantities, such as use of the derivatives and propagation of influences instead of calculation of the magnitudes of the quantities. However, ambiguity can be a useful tool for education. Branches in the envisionment graph provide the student with alternative outcomes of the same problem.

It has been shown that the guidelines for the modelling process are very useful. Starting with a kernel of model fragments representing basic concepts (about populations), it was possible to expand the library to incorporate environmental factors and knowledge about more complex ecological systems (communities). Initially, the modeller has to implement a relatively large number of model fragments to obtain some running models. This changes after the kernel of model fragments representing the core of the domain knowledge is implemented. Then few model fragments need be added in order to increase the number of running models.

The quality of the representation can be evaluated by comparing the number of running models that can be derived from the library with the number of model fragments. A general library including the most basic concepts allows a large number of running models. More specific representations on the other hand require a large number of model fragments to support a small number of simulations. In summary, the goal of the modelling process is to have a library associated with a large number of initial scenarios, and a large number of running models, producing simulations of a manageable size.

The next chapter will show how the qualitative models based on both the mathematical (Chapter 5) and the causal structure (Chapter 6) can be used to support different types of explanation.

Chapter 7 Deriving explanations from qualitative models

In this chapter a qualitative description of the physical structure is shown to have the potential for supporting explanations about the system and its behaviour. This is possible because qualitative models provide access to the concepts used during the problem solving activity, provide clarity in the operations carried out during reasoning process, and support prediction of behaviour based on the analysis of the structure of the system Bredeweg & Winkels (1994; 1997).

There are two aspects to generating explanations in learning environments: the computer system has to decide *what* to say in the explanation and *how* to do it. The former should take into account the question proposed by the student and the domain knowledge represented in the knowledge base. An example of the problems involved in this task is presented by Rickel & Porter (1997), who used the compositional modelling approach (Falkenhainer & Forbus, 1991) for selecting model fragments in the library. Decisions about what to say require a set of tactics and strategies about the best way to construct the answer, taking into account the context of the question, the educational objectives and the student model (see, for example, Vadillo *et al.*, 1997).

In qualitative models, the modelling primitives may be the basis for deriving explanations from the physical structure of the system. The utterances that constitute the explanation should map, at the lowest level, to these. Given that the system's components and the reasoning process underneath the problem solving are explicitly represented with these primitives, it is possible to ground explanations on them. The discourse strategies take care of rationale and didactic principles at a higher level.

This approach has been investigated in a joint effort between the author, Bert Bredeweg and Radboud Winkels[26]. It combines qualitative modelling and simulation in

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[26] The author implemented the models described in Chapter 6 in a joint work with Bredeweg. The machinery for the explanation generator used in this chapter was totally implemented by the author, except for the example presented in section 7.9 (' Planning explanations'), which was implemented in DDP by Winkels. The author also developed the topics presented in sections 7.4-7.6. All the examples of explanations presented in this chapter are produced by the above mentioned explanation generator. Some editing in the explanations was made for the sake of readability.

GARP (Bredeweg, 1992), with didactic discourse planning in DDP (Winkels, 1992). Qualitative models developed in GARP (such as those described in Chapter 6) can be questioned by the students, and these questions can be answered by a generic didactic discourse planner. Several questions can be asked during the simulation. These questions are linked to 'information needs', the topics of the discourse. According to these topics, DDP plans sequences of utterances. The preliminary results were presented in Salles *et al.* (1997).

This chapter is concerned with the organisation into topics of the domain knowledge represented in the models. It is shown that this knowledge can be represented in terms of simple topics (for example, the value of a quantity), and of more complex topics (such as the notion of state) which are built by combining these simple topics.

In section 7.1, the requirements for the explanations are discussed. Section 7.2 presents a particular type of explanation, in which the calculations during a simulation are traced and domain knowledge is not explicitly referred to. The use of domain knowledge in the explanations is discussed in the subsequent sections. In section 7.3 a typology of questions is presented, with some examples. In section 7.4 the topics related to the description of the physical structure of the system are presented. These topics are combined to build the notion of state, which is discussed in section 7.5. In section 7.6 the topics relative to the description of the behaviour of the system are presented. How these topics can be used to answer questions is discussed in section 7.7. An example of explanations in a different domain is presented in section 7.8. Finally, section 7.9 shows how explanations can be planned according to the strategies and tactics implemented in DDP.

7.1 Requirements for explanations

According to Valley (1992), the factors that affect the structure and content of an explanation generated by an expert system include its *target*, its *type*, the *knowledge needed* to provide it and the *interaction* between the user and the explanatory facility.

The target of an explanation is the user. In educational contexts, the explanatory facility must be able to identify novices and more advanced students when deciding the type, the structure and the contents of the explanation.

Valley identifies two main types of explanation: system-based and domain-based explanations. The former describes what happened during the consultation with an expert system. It is therefore a tracing of what rules have been fired, and what facts have been deduced. In the context of simulations, system-based explanations give an account of the values of the quantities, and of how they were calculated. According to the framework proposed in Chapter 4, this type of explanation draws on the mathematical and the causal structures of the system. Domain-based explanations refer to domain knowledge explicitly represented. They explore the conceptual structure, and can be used to complement system-based explanations: whereas those explain how the values are calculated, domain knowledge can be used for explaining why calculations have been done. In the context of the present work, it is assumed that both system and domain-based explanations must be available to students.

The knowledge needed in an explanation may refer to domain concepts and to principles of problem solving. This is a problem of knowledge representation. For example, many early expert systems such as GUIDON (Clancey, 1982) used production rules to represent knowledge. These rules are found to be inadequate for generating coherent and informative explanations, because knowledge is compiled and reduced to premises and conclusions, and there is no way of distinguishing different types of knowledge. However, the use of meta-rules to classify the rules according to their function (as in NEOMYCIN) may improve the explanations generated from the knowledge base (Clancey, 1983). Sometimes short explanations are better than longer ones. Decisions of this type require information about the student, which can be acquired explicitly (by the analysis of the question being formulated), or implicitly (by consulting the student model or the context of the question). Both aspects are addressed in GARP and DDP. These two systems were developed according to the KADS methodology (Breuker & Wielinga, 1989), which distinguishes between domain, inference, task and strategic knowledge. DDP also includes a coach and a student model, which take care of the level of details included in the explanation. For details, see Bredeweg (1992) and Winkels (1992).

The interaction requirement refers to the methods by which explanation is requested by and presented to the student. DDP accepts questions formulated by filling in templates or by using menus. The answers are provided in natural language, using rhetorical schemes (see section 7.9).

We can add to these some requirements determined specifically by the domain. To understand how ecological knowledge can be organised for supporting explanations in an educational context, it is important to consider the different levels at which biological systems can be studied. Biological systems can be classified according to different levels of granularity from the sub-cellular level up to the biosphere, as follows:

sub-cellular - cell - tissue - organ - individual - population - community - ecosystem - biosphere

Although all these levels are intrinsically linked and influences can flow in any direction, ecology is concerned mainly with the levels ranging from population up to biosphere. As a general principle, given a fact at any level, we should look for explanations for this fact in levels at the left side of that one. Conversely, consequences from a given fact might be found on the levels on the right side. That is, the chain of causality goes mainly from the left to the right side of this gradient of hierarchical levels. For instance, something that happens at the population level can be explained by facts occurring at the individual level, and explanations for these facts in turn can be found at organs, cells and sub-cellular levels. Viewed from the other side, the consequences of populational phenomena can affect the community where this population is inserted, the ecosystem, and maybe the biosphere.

One could object to the generality of this rule, because there is evidence that influences from higher levels act upon lower levels. For example, some experiments show that populational density can affect the reproductive behaviour of individuals. However, even in this case explanations for individual behaviour have to refer to lower levels. Given that ecological laws are not well understood, this hierarchy associated with the organisational level of biological systems may constitute the "first principles" in the reasoning of ecological and agricultural modellers (Plant & Loomis, 1991).

7.2 Deriving system-based explanations from qualitative models

As mentioned in Section 7.1, system-based explanations describe what has happened during a consultation with an expert system, for example, which rules have been fired and which facts have been deduced (Valley, 1992). In the present case, this type of explanation provides an account for the calculations, with all the intermediate steps and values of the quantities. Although not using explicit domain knowledge, this is important for explaining the simulation itself.

An example of this type of explanation comes from a simulation with the model Life Cycle II (Chapter 5, section 5.3). Suppose the students want to evaluate the population size in the next time unit, running a simulation starting with a certain intial scenario. A series of questions elicit the initial values for the quantities number of plants (many), number of flowers per plant (small), number of seeds per flower (medium), temperature (cold) and soil water (dry).

A system-based explanation about this simulation would be the trace of the calculations. The answer may be a complete list of the quantities in the model, including the input from the student and intermediate quantities, or only the quantities most important to the calculations. For example, Figure 7.1 shows a simulation in which the student wants to calculate the size of the population in the next time unit:

| ?- callnextpop.

(Here the student is asked to enter the inputs)

Question: How many plants does the area have? (very_few - very_many)
Answer: many.

Question: How many flowers per plant? (small / medium / large)
Answer: small.

Question: How many seeds per flower? (small / medium / large)
Answer: medium.

Question: What is the temperature? (very_cold - very_hot)
Answer: cold.

Question: What is the soil water condition? (very_dry - very_wet)
Answer: dry.

(*Final answer*)
Given that number of plants is large, (*which is part of the input*)

Then the number of established plants is very_small
and the number of dead plants is medium.
Growth rate is negative: established is smaller than dead plants.
Next time step number of plants will be medium. (*which are the outputs*)

yes

Figure 7.1 An example of system-based explanation. Comments are added in italics.

Simulation, as discussed in Chapter 4, relies on value calculation. These values can be seen as the 'facts' upon which the explanatory discourse is created. In this sense, system-based explanations such as the one shown above are very important: tracing tells us what the 'facts' are, and the sequence in which they occurred.

The model Life Cycle II is based on the mathematical structure of the system, and there is no representation of the concepts involved. It is therefore impossible to derive domain-based explanations from the model itself. As part of the investigation of explanations proposed in this thesis, an *ad hoc* knowledge base of concepts and inference machinery was developed, in order to complement these system-based explanations with explanations based on domain knowledge. This work is discussed in Salles et al. (1996).

The limitations of production rules for explanations in educational contexts have already been mentioned (section 7.1). A more interesting approach is the use of the knowledge explicitly represented in qualitative models to support domain-based explanations. This point will be discussed in the following sections (7.3-7.8). Explanations in general start with answering questions. A typology of questions and a discussion about how they can be used for selecting relevant knowledge are presented in the next section.

7.3 What are the questions?

The most obvious way of explaining something is by answering questions. However, it is not so obvious how to formulate the answer. Explanations based on pre-stored textual information have been seen as an inadequate approach for learning environments for many reasons. First, this approach does not take into account the student's needs, their knowledge level and the context of the explanation. Second, the modeller cannot anticipate all the possible questions or build a representation of the domain to provide specific answers. The EUROHELP project[27] (Breuker, 1990) relies on a pure domain representation and explores the possibilities of automatic text generation.

The alternative is to create a typology of questions for guiding the selection of relevant knowledge in the knowledge base, for example according to relations between the concepts of the domain (Acker et al., 1991) or the intentions of the user (Hartley et al., 1990). The typology proposed by (Hartley et al., 1990) was used in the EUROHELP project for creating formal internal representations of the questions, that become part of the knowledge used to answer the question. The questions were linked to 'information needs', that is, the topics of the discourse, and to appropriate strategies for building the answer. On the basis of these topics, the discourse planner plans sequences of utterances, taking into account such things as the student's beliefs and the state of the discourse process.

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[27] DDP (Winkels, 1992) was developed as part of the EUROHELP project.

The typology proposed by Hartley et al. (1990) is based on experiments and observations on how users of information processing systems and experts interact while receiving / giving help. Although developed in a different context, this typology is very general and can be applied to the present work. The following classes of questions are identified: Elaboration, Enablement, Evaluation and Exploration.

1) Elaboration questions are requirements for descriptions of the objects in the system. Typical examples of Elaboration question can be illustrated by incomplete sentences such as 'What is ...?' and 'What are the parts of...?'. A special type of Elaboration question involves the comparison between two objects of the same kind with respect to similarities and differences between them.

2) Enablement questions request method plans to achieve certain goals, and the answers to this type of questions should enable the user to achieve those goals. The typical question of this type is 'How do I ...?'. This is the most frequent type of question users ask to Help Systems. However, given that the task to be performed in the learning environment described here is behaviour analysis, this type of question is not applicable.

3) Evaluation questions are requests for causal explanations. They relate specifically to the understanding of the system's response to a user's action. The typical question is 'When I did ..., what happened?'. A variation of this type of question may be interesting for the understanding of the simulations described here. For example, the question 'Why did... happen?' may be used to make explicit the causal relations between the quantities.

4) Exploration questions are causal questions relating hypothetical actions and their effects. The typical format is 'What will happen if ...?'. This can be seen as the main question posed at the beginning of the simulations.

In our explorations of how GARP and DDP can be combined in a learning environment (Salles et al., 1997), several routines for question-answering were implemented[28]. Given the framework chosen (GARP) and prediction of behaviour as a task, students can ask the following questions about a simulation:

1. What are the objects, quantities, quantity values, and quantity relations involved in a particular model fragment or state of the simulation?
2. What are the conditions for a particular view or process to become active? These conditions in general include some inequalities between quantities.
3. What are the initial causes of change in the current state? This is asking about processes and agent models that can cause change. As explained in Chapter 4 (section 4.3), initial causes of change are modelled as direct influences between quantities.
4. How does change propagate to other quantities in the present state? This is asking about indirect influences between quantities (proportionalities), and possibly new direct influences.
5. How does a particular quantity change over states? This is asking about values of magnitudes and derivatives of a quantity. Given the envisionment graph produced by GARP, it is not difficult to find the values for a specific quantity in every state of a complete simulation.
6. How can a particular view (or process) be compared with another view (or process)? This is asking about differences and similarities between the objects, quantities, quantity values and quantity relations in different views or processes.
7. How can a particular state of the simulation be compared with another state? This is asking about differences and similarities between the objects, quantities, quantity values, quantity relations, active views and active processes in two states of the simulation.

Some examples of how these questions can be answered are presented in sections 7.4-7.7.

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[28] See footnote number 26.

In DDP questions are specified according to the question type, the conditions for their use, a template for each question type and a procedure for generating the answer. There is a logical order in the questions. For example, propagation of change cannot be explained before students know about initial causes of change. Therefore questions have preconditions attached to them, that check whether the necessary prerequisite information is already available. Finally, the procedures needed for generating an answer are specified in the question type.

For example, a question about the propagation of the effects of processes can be specified as follows:

Type:	propagation of influence X within A state
Conditions:	Influence X has been introduced
Template:	'How does X propagate in this state?'
Procedure:	Find all proportionalities between the quantity that is influenced in X and other quantities. Look recursively for influences or proportionalities with these other quantities until no more can be found.

Given a question, it is necessary to determine what to say, i.e. what topics should be explored to fulfil the student's information need. This is what McKeown (1985) calls 'the relevant knowledge pool', or Winkels (1992) calls the 'topicalization process'. In DDP the interpretation of a question is associated with information, coming from other modules, about deficiencies in the user's performance of some task.

Given that the task the students are supposed to perform in the present work is prediction of behaviour, the generic diagnostic process that tries to infer the 'student's information need' when they ask a question developed in DDP is not applicable. A procedure to determine the initial topic is directly linked to the questions. These initial topics can be shortened or extended by the discourse planner when needed (see section 7.9).

The workings of such a 'topicalization' procedure is illustrated for the simulation described in Chapter 6 (section 6.3), about succession in the cerrado communities. The scenario specifies a population of grass (population3), and a human agent called fire decreaser1, which causes a decrease in fire_frequency1. Now the question:

'How does the negative influence of fire_decreaser1 on fire_frequency1 propagates in this state?'

leads to a topic in the following way: first find all the proportionalities between fire_frequency1 and other quantities. There is only one in this state, a negative proportionality with litter1 (fire will burn litter on the ground). Now look for influences or proportionalities on this other quantity: positive proportionalities with humidity1 and nutrient1 (litter provides nutrients and will keep the soil moist), negative proportionalities with light1 and temperature1 (litter will block light and warmth). Again, for all these quantities, look for influences or proportionalities on them, until no more influences are found. The result is a list of qualitative proportionalities and direct influences linking these quantities as shown in the causal graph of Figure 6.5. This example is further developed in section 7.9.

As mentioned above, after inspecting the successive states of a simulation, the student can ask questions that can lead to topics ('information needs') to be handled by the discourse planner. The discourse strategies take care of general rationale and didactic principles involved in the explanation at the higher levels. However, at the lowest level, utterances have to map onto the knowledge representation implemented in the qualitative simulator (GARP).

In order to translate GARP's modelling primitives into topics of the explanatory discourse, each modelling primitive was classified according to the following aspects:

a) the type of primitive (Type);

b) the knowledge representation of the primitive in GARP (KR);

c) information that should be either known (because it is represented in the student model or the discourse model of the current session) or given for the primitive to be used (Known);

d) other necessary conditions for the primitive to be used, referred to in the current state of the simulation (e.g. the value of a derivative) and in the current state of the discourse (e.g. topic in focus) (Cond);

e) the natural language expression for the primitive when the conditions are met (NL).

For example, primitives for representing the values of quantities can be classified as follows:

Type:	explaining the values of magnitude and derivative of a quantity;
KR:	value(QuantityInstanceName, QuantitativeValue[29], MagnitudeValue, DerivativeValue)
Known:	QuantityInstanceName
Cond:	DerivativeValue is minus; focus on the QuantityInstanceName
NL:	"QuantityInstanceName has currently the value MagnitudeValue and is decreasing."

Similar representations were made of other GARP primitives (see the Appendix). They can be combined for supporting explanations about knowledge encoded in these primitives as they appear in any state of the simulation. For instance, if the quantity number of trees has value < medium, minus > in a particular state, the Prolog predicates

number_of(tree1, number_of1, _, zlmhm)
value(number_of1, unknown, medium, min)

can be converted in an utterance such as

"number_of1 is a quantity number_of of tree1.
It currently has the value medium and is decreasing."

This combination of question type and topics of knowledge can be used for generating domain-based explanations. A more detailed taxonomy of the questions and associated topics is presented in section 7.7.

In Chapter 4 (sections 4.1 and 4.2) the knowledge required for representing ecological (physical) systems in qualitative models was discussed. The next three sections (7.4 - 7.6) illustrate how these requirements can be transformed into topics of the didactic discourse[30].

[29] Quantitative values were not used in any model described in this thesis.
[30] See footnote number 26.

7.4 Explaining the physical structure of the system

Topics are self contained pieces of knowledge. They may represent concepts with different levels of complexity. For example, the notion of Quantity Space is expressed in the topic QUANTITY SPACE (in this chapter, the name of the topic is written in capital letters). More complex topics can be constructed by combining simpler topics. For example, the topic QUANTITIES includes the topic QUANTITY SPACE and topics about the object to which the quantity is related, its instance name and the type of quantity.

Each topic described in this and the following sections includes all the related topics. However, when the actual explanation is produced some topics can be omitted, depending on the context of the explanation and information available in the student model.

In this section, topics related to the description of the physical structure of the system are presented. They match with the requirements defined in Chapter 4, sections 4.1 and 4.2. Thus they refer to objects, quantities, situations and mechanisms of change. The examples presented in this section refer to the model Life Cycle III (see Chapter 5, section 5.5).

7.4.1 Objects

In the topic OBJECTS, objects are identified by a generic name (OBJECT NAME) and an instantiated name (OBJECT INSTANCE NAME). Given that objects are related to other objects by means of *isa* hierarchies (Chapter 4, section 4.3), they may be instances of more generic objects. This relation is represented by the topic ISA OBJECT. Some of the object's attributes may be explicitly represented in the model. For example, the object can be part of another object, or may consist of other objects. This knowledge is encoded in the topic OBJECT HAS_ATTRIBUTE. Finally some quantities may be associated with the object described in the topic OBJECT QUANTITIES.

The topic OBJECTS is organised as follows:

```
                                   objects
                                      |
          -----------------------------------------------------------------
          |              |            |                 |                  |
   (object name)  (obj. inst. name)  (isa object)  (obj has attribute)  (obj qtty)
```

As mentioned above, a topic may be related to other topics. The semantics of the topic can be expressed by means of phrases that explicitly link the main topic and the subtopics. For example,

---

OBJECTS:

there is an object named OBJECT NAME
the object has an instantiated name OBJECT INSTANCE NAME
it is defined by the relation ISA OBJECT
and by the attributes OBJECT HAS_ATTRIBUTE
the properties of the objects are represented by OBJECT QUANTITIES

An example of how this topic supports a natural language utterance is presented below. Here two objects (population and plant) are related by a relation type 'consists of':

there is an object called population1
which is an instance of population

there is an object called plant1
which is an instance of plant

population1 consists of plant1.

plant1 has quantities {number_of_plant, number_of_flower_per_plant, number_of_flower, number_of_seed_per_flower, number_of_seed, number_of_dead, number_of_established}

7.4.2 Quantities

Quantities are described in the topic QUANTITIES by their generic name (QUANTITY NAME), and by their instantiated names (QUANTITY INSTANCE NAME). Quantities are associated with a particular object, referred to by its instantiated name (OBJECT INSTANCE NAME). Note that the quantity is associated with a particular object. This way it is possible to have other instances of the same generic object associated with instances of the same quantity. Another topic (QUANTITY TYPE) refers to the type of quantity (for example, continuous, discrete, numerical). All the quantities included in the models described here are continuous. An important topic is the set of qualitative values associated with that quantity (QUANTITY SPACE).

These topics are related to the topic QUANTITIES as shown below:

```
                              quantities
                                  |
        -----------------------------------------------------------
        |              |               |              |              |
   (qtt name)   (qtt inst name)  (obj inst name)  (qtt type)    (qtt space)
```

The semantics of the topic can be expressed as follows:

QUANTITIES:

the quantity is associated with an object OBJECT INSTANCE NAME
the quantity has an instantiated name QUANTITY INSTANCE NAME
the quantity type is QUANTITY TYPE
the quantity has Quantity Space QUANTITY SPACE

For example,

plant1 has quantity number_of_plant
instantiated as number_of_plant1

number_of_plant1 is a quantity type continuous
and can take on the values {very_few, few, medium, many, very_many}

7.4.3 Quantity values

The topic QUANTITY VALUES is associated with four topics. The quantity is identified by an instantiated name (QUANTITY INSTANCE NAME). Its qualitative value may be associated with a quantitative value, represented in the topic QUANTITATIVE VALUE. Given that the quantities described in this thesis are strictly qualitative, this topic is not used here. The quantity's magnitude is expressed in the topic MAGNITUDE VALUE, while its derivative is expressed in the topic DERIVATIVE VALUE.

The topic QUANTITY VALUES is organised as follows:

```
                         quantity values
                                |
          ---------------------------------------------------
          |                |                |               |
   (qtty ins name)    (quant val)     (magnit val)     (deriv val)
```

QUANTITY VALUES:
the quantity instantiated name is QUANTITY INSTANCE NAME
the quantitative value of the quantity is QUANTITATIVE VALUE
the current value of the quantity's magnitude is MAGNITUDE VALUE
the current value of the quantity's derivative is DERIVATIVE VALUE

An example of an explanation using these topics is

the quantity number_of_plant1
the quantitative value of number_of_plant1 is unknown
the magnitude of number_of_plant1 is few
and derivative of number_of_plant1 is positive

7.4.4 Quantity relations

The topic QUANTITY RELATIONS refers to the four types of relations defined in Chapter 4, section 4.2. INEQUALITIES comprises comparisons between the magnitudes and the derivatives of the quantities. CAUSAL RELATIONS includes all sorts of causal dependencies between quantities. Functional relations are expressed in the topic FUNCTIONAL RELATIONS. The mathematical relations necessary for calculating the values of the quantities are included in the topic CONSTRAINTS.

```
                 quantity relations
                         |
        ------------------------------------------
        |          |           |           |
      (ineq)  (causal rel)  (func rel)   (const)
```

QUANTITY RELATIONS:

inequalities that hold in the state are INEQUALITIES
causal dependencies that hold in the state are CAUSAL RELATIONS
functional dependencies that hold in the state are FUNCTIONAL RELATIONS
mathematical relations that hold in the state are CONSTRAINTS

Each of these topics in turn can be split into more detailed topics. Each will be described below.

7.4.4.1 Inequalities

The topic INEQUALITIES includes topics related to comparisons between the magnitude and the derivative of the quantities. They can be organised as follows:

```
                                inequalities
                                     |
   ------------------------------------------------------------------------
   |        |          |          |          |         |          |          |
(equal) (greater) (equal /   (smaller) (equal/   (der equal) (der greater) (der smaller)
                   greater)             smaller)
```

INEQUALITIES:

equal quantities are described as EQUALITY
greater quantity is described as GREATER
greater or equal quantity is described as EQUAL GREATER
smaller quantity is described as SMALLER
smaller or equal quantity is described EQUAL SMALLER
equal derivatives of quantities are described as DERIVATIVE EQUALITY
greater derivative is described as DERIVATIVE GREATER
smaller derivative is described as DERIVATIVE SMALLER

Some examples of utterances based on these topics are

number_of_plant1 is equal to few
number_of_flower1 is greater than number_of_plant1
number_of_seed11 is equal or greater than number_of_flower1
number_of_dead1 is smaller than number_of_plant1
number_of_established1 is equal or smaller than number_of_plant1
derivative of number_of_plant1 is greater than zero

Inequalities[31] are used for comparing magnitudes and derivatives. Although it is possible to compare magnitudes of derivatives using the available modelling primitives, and then generate explanations such as 'born1 is increasing faster than immigrated1', this approach is not explored in this thesis. Inequalities involving derivatives are always used when comparing their values with zero, as shown in the example above. In this case, it means 'the population is increasing'.

7.4.4.2 Causal relations

The topic CAUSAL RELATIONS includes four types of relations: positive and negative direct influences, and positive and negative proportionalities. The first two

---

[31] Inequalities is used here as a broad term, which includes the 'equal' relation.

relations represent initial causes of change in the system, whereas the other two are responsible for the propagation of changes to indirectly influenced quantities.

```
                          causal relations
                                 |
          ------------------------------------------------
          |              |              |              |
     (pos dir inf)  (neg dir inf)  (pos prop)     (neg prop)
```

CAUSAL RELATIONS
positive direct influences are POS DIRECT INFLUENCE
negative direct influences are NEG DIRECT INFLUENCE
positive indirect influences are POS PROPORTIONALITY
negative indirect influences are NEG PROPORTIONALITY

An example of a positive direct influence is

number_of_plant1 is directly and positively influenced by process population growth at a rate equal to growth_rate1
(growth_rate1 is a positive direct influence on number_of_plant1)

If this is the only direct influence on number_of_plant1,
when growth_rate1 has a positive value,
the derivative of number_of_plant1 gets the same value
and plant starts to increase.

Similarly, an example of a positive indirect influence is

number_of_seed1 is a positive indirect influence on
number_of_germinated_seed1

If number_of_seed1 is the only influence on number_of_germinated_seed1
when number_of_seed1 is increasing, then number_of_germinated_seed1
increases as well

7.4.4.3 Functional relations

The topic FUNCTIONAL RELATIONS include the causal relations mentioned above, and correspondences between either specific values or the whole quantity spaces of two quantities.

```
                         functional relations
                                  |
              ------------------------------------------
              |                   |                   |
       causal relations    (value corresp)    (quant space corresp)
```

```
---------------------------------------------------
FUNCTIONAL RELATIONS
        functional relations can be also CAUSAL RELATIONS
        correspondence between values are VALUE CORRESPONDENCES
        correspondence between quantity spaces are QUANTITY SPACE CORRESPONDENCES
---------------------------------------------------
```

Example:

the value low of number_of_seed1 corresponds to the value low of number_of_germinated_seed1

7.4.4.4 Constraints

The topic CONSTRAINTS defines details of the mathematical operations between quantities. In the models described in this thesis, the constraints are represented by the operations addition, subtraction, and multiplication, and by the effects of the operators increase, decrease and invert values[32] (see Chapter 4, section 4.3). Some (or all) of these topics can be combined in the last topic, qualitative equation.

[32] Only addition and subtraction are currently implemented in GARP. The other constraints were used in the models described in Chapter 5.

```
                    constraints
                         |
       ------------------------------------------------
       |      |        |       |       |          |
     (add) (subract) (mult) (incr)  (decr)  (qual equation)
```

```
--------------------------------------------------
CONSTRAINTS
        addition of quantity values is ADDITION
        subtraction of quantity values is SUBTRACTION
        multiplication of quantity values is MULTIPLICATION
        the value of a quantity can be increased by INCREASE VALUE
        the value of a quantity can be decreased by DECREASE VALUE
        the value of the quantity can be inverted by INVERT VALUE
        the constraints are related in qualitative equations QUALITATIVE EQUATION
--------------------------------------------------
```

Examples:

low plus high equals high
high minus low equals high
very_high times medium equals very_high
low increased one step equals medium
very_high decreased one step equals high
the inverted value of high is low

number of flower1 equals the number_of_plant1 multiplied by the number_of_flower_per_plant1

7.4.5 Situations and mechanisms of change

As discussed in Chapter 4 (section 4.3), situations and mechanisms of change are represented, respectively, as views and processes. They use a similar syntax, and describe knowledge around the notions of objects, quantities and quantity relations. However, their effects are different: whereas views describe general relations between the modelling components, processes are assumed to be the only cause of change in the system.

Views and processes are the two main types of model fragments in QPT-based models. According to the 'one concept, one model fragment' rule (section 4.5), a model fragment should express a stand-alone concept. Therefore each model fragment is associated with a topic called MAIN CONCEPT. This topic includes two other topics, CONDITIONS and GIVENS, which express the conditions under which the topic is applicable, and the effects it produces in the system respectively.

```
                   main concept
                         |
         ---------------------------------
         |               |               |
   concept name     conditions        givens
```

MAIN CONCEPT:

the main concept name is CONCEPT NAME
the conditions for applying the concept are CONDITIONS
the consequences of applying the concept are GIVENS

Both CONDITIONS and GIVENS consist of one or more of the four topics presented so far: OBJECTS, QUANTITY, QUANTITY VALUES, or QUANTITY RELATIONS (sections 7.4.1 - 7.4.4). In this way, the topic MAIN CONCEPT expresses both the conditions for the concept to apply and the effects on the system in terms of objects and their properties.

For example, process *Population growth* (Chapter 5, section 5.5) can be described as follows (repeated statements and instance names were omitted):

population growth
is a process affecting the population of plant

there is an object cerrado
there is an object population
there is an object plant
cerrado has_population population
population consists of plant

plant has_quantity number_of_plant
it is a quantity type continuous
and it can take on the values
{very_few, few, medium, many, very_many}

plant has_quantity number_of_established_plant
plant has_quantity number_of_dead_plant

population growth is active when
the number_of_plant is equal or greater than very_few
and the view Plant Population holds
and the view Environmental Conditions holds

Being active, population growth process has the following effects:
plant has_quantity growth_rate

growth rate is indirectly and positively influenced by
number_of_established_plant
growth rate is indirectly and negatively influenced by number_of_dead_plant

number_of_plant is directly and positively influenced by growth_rate

If this is the only influence on number_of_plant
when immigrated1 has a positive value,
the derivative of number_of_plant gets the same value
and number_of_plant starts to increase.

7.5 Explaining the notion of state

The most important topic for describing the behaviour of the system is BEHAVIOUR EXPLANATION. Given that behaviour is seen as a sequence of states, the notion of state is central to the generation of explanations about the system's behaviour. Accordingly, the topic STATE DESCRIPTION includes knowledge about how the objects and their properties are arranged in each particular state.

State descriptions are useful for supporting the analysis of the simulation. This analysis is a two-step process. Initially the focus is on the forces acting within the system during the time period corresponding to a state (intrastate analysis)[33]. The second step focuses on the transitions to other states (interstate analysis), depending on the balance

[33]The terms *intrastate* and *interstate analysis* were used by de Kleer & Brown (1984) in a slightly different way. For these authors, intrastate analysis refers to the combination between each qualitative state of each component and each qualitative state that all the other components may have. This analysis shows all the possible states for the system . Interstate analysis is the next step, when all the inconsistent states of the components are excluded. As a result, all the transitions from a particular state are determined.

of these forces. The knowledge involved in these steps is expressed in the topics INTRASTATE ANALYSIS and INTERSTATE ANALYSIS. The latter is essential in two important activities for the understanding of the system's behaviour: prediction (anticipating future states on the basis of the current state) and postdiction (explaining the current state in terms of the previous state).

These high level topics can be combined as follows:

```
                        behaviour explanation
                                  |
      ------------------------------------------------------------
      |                           |                             |
state description          intrastate analysis            interstate analysis
                                                                 |
                                                      -----------------------
                                                      |                     |
                                             behaviour prediction   behaviour postdiction
```

```
-------------------------------------------------
BEHAVIOUR EXPLANATION:
        current state of the simulation can be described STATE DESCRIPTION
        analysis of how changes initiate and propagate is INTRASTATE ANALYSIS
        comparative analysis of states is INTERSTATE ANALYSIS
-------------------------------------------------
```

Each of these topics is examined below. At the end of the section an example illustrates the use of these topics.

7.5.1 State description

The topic STATE DESCRIPTION consists of seven topics, including knowledge about the objects and their properties involved in the state (OBJECT, QUANTITIES, QUANTITY VALUES, QUANTITY RELATIONS). These topics were already mentioned (sections 7.4.1 to 7.4.4) and are not repeated here.

Two topics are particularly important in describing the main concepts about the system in that state: VIEW STRUCTURE and PROCESS STRUCTURE. The view structure consists of the set of model fragments (views) that describe the system in the current state. The process structure is a set of active processes and agent models in that state. As mentioned above, model fragments are described in the topic MAIN CONCEPT(section 7.4.5). It follows from that that the view and the process structure represent the main concepts describing the system in that particular state. In terms of the framework proposed in Chapter 4 (section 4.2), this is the conceptual structure of the system.

Describing the state with main concepts about views and processes has another feature of considerable importance for explanations. Main concepts are implemented in terms of conditions and givens (section 7.4.5). Therefore it is possible to explain the state in terms of the conditions for the state to hold, and to explain the effects of the state for the behaviour in terms of the givens introduced by the main concepts. This point will be explored in section 7.7.

The topic STATE DESCRIPTION can be organised as follows:

```
                                state description
                                        |
        ---------------------------------------------------------------------------
        |          |          |              |               |            |             |
state identif   objects   quantities   quantity values   qtty relat   view struct   process struct
```

STATE DESCRIPTION:

current state of the simulation is state STATE IDENTIFICATION
current state includes the following objects OBJECTS
these objects are represented by quantities QUANTITIES
these quantities have values QUANTITY VALUES
they are structured by means of the relations QUANTITY RELATIONS
the global situation is described by the VIEW STRUCTURE
the situation can change because of the PROCESS STRUCTURE

7.5.2 State identification

The topic STATE IDENTIFICATION situates a particular state within the simulation. The state is identified in terms of the previous state (maybe more than one) and states that follow from that one (maybe one, maybe none), and the initial scenario. Obviously, this is a recurring set of topics in explanation.

STATE IDENTIFICATION is organised as follows:

```
                         state identification
                                  |
      ------------------------------------------------------------
      |                |                    |                |
(state N)      (state N – 1)          (state N + 1)     initial scenario
```

```
-------------------------------------------------------
STATE IDENTIFICATION:
        current state of the simulation is state STATE N
        it comes from another state STATE  N – 1
        and originates further state STATE N + 1
        in a simulation which started with initial scenario INITIAL SCENARIO
-------------------------------------------------------
```

7.5.3 Initial scenario

The topic INITIAL SCENARIO describes the initial conditions of the simulation. This is done in terms of objects, quantities, and quantity values. The initial scenario is therefore a simplified description of a state, without the view and the process structures.

```
                    initial scenario
                           |
            ------------------------------------
            |          |          |           |
     ini sce name   objects   quantities   qtty values
```

INITIAL SCENARIO:

the initial scenario name is INITIAL SCENARIO NAME
the initial scenario includes the objects OBJECTS
these objects are represented by quantities QUANTITIES
these quantities have values QUANTITY VALUES

7.5.4 View Structure

The topic VIEW STRUCTURE is an overview of the main concepts used to describe general knowledge about the system in a particular state. It consists of views selected to comprise the state.

view structure
|
_
|
active views

VIEW STRUCTURE:

active views in state is ACTIVE VIEWS

7.5.5 Process Structure

The topic PROCESS STRUCTURE includes all the model fragments representing active processes and agent models in that particular state.

process structure
|
_
|
active processes

PROCESS STRUCTURE:

active process in state are ACTIVE PROCESSES

Ultimately, the topics VIEW STRUCTURE and PROCESS STRUCTURE are the description of the conceptual structure of the system in a particular state. Therefore they are the core of the explanatory discourse.

```
                 conceptual structure
                          |
                  --------------------
                  |                  |
           view structure     process structure
```

7.5.6 An example of state description

The example presented here is a description of a state in the simulation with the model *Life Cycle III* (Chapter 5, section 5.5):

1) Which state is this?

this is state 1
it comes from the initial scenario

The model *Life Cycle III* describes just one state, so there are no other states to refer to as 'previous' and 'future' in STATE IDENTIFICATION. The INITIAL SCENARIO is built according to the input values given by the user.

2) What are the main concepts for describing the state?

plant_population
environmental_conditions
population_growth

The answer to this question is based on the topics VIEW STRUCTURE (which identifies *plant population* and *environmental conditions* as the active views), and PROCESS STRUCTURE (which consists only of *population growth*).

3) What are the objects involved in the current state?

there is an object called cerrado1
which is an instance of cerrado

there is an object called population1
which is an instance of population

cerrado1 has_population population1

there is an object called plant1
population1 consists of plant1.

In this case, the topic OBJECTS was used to identify the main types of objects, and the topic ISA OBJECT to identify the instances of each object. The relations between the objects are captured in the topic OBJECT HAS_ATTRIBUTE. The quantities related to these objects are shown in the next question.

4) What are the quantities involved?

plant1 has quantity number_of_plant1
plant1 has quantity flower_per_plant1
plant1 has quantity number_of_flower1
plant1 has quantity seed_per_flower1
plant1 has quantity number_of_seed1
plant1 has quantity number_of_germinated_seed1
plant1 has quantity number_of_established1
plant1 has quantity number_of_dead1
plant1 has quantity growth_rate1

cerrado1 has quantity soil_water1
cerrado1 has quantity soil_temperature1

This answer is based on parts of the topic QUANTITY, which identifies the object to which the quantity is related. A full description of a quantity is presented in section 7.4.2. The quantity values were omitted.

5) What are the conditions for this state to hold?

number_of_plant1 is equal or greater than very_small
soil_water1 is equal or greater than very_dry
soil_temperature1 is equal or greater than very_cold

The topic QUANTITY RELATIONS is the basis for answering this question, particularly the topic INEQUALITIES.

6) What are the primary causes of change?

> *number_of_plant1 is directly and positively influenced by process population growth at a rate equals to growth_rate1*
>
> *If this is the only influence on number_of_plant1,*
> *when growth_rate1 has a positive value,*
> *the derivative of number_of_plant1 gets the same value*
> *and plant starts to increase.*

The topic PROCESS STRUCTURE is instantiated to the single process *Population Growth*. This is the only primary cause of change in this state.

7) How does change propagate within the system?

> *number_of_plant1 is an indirect influence on number_of_flower1*
> *number_of_flower1 is an indirect influence on number of seed1*
> *number_of_seed1 is an indirect influence on number_of_germinated seed1*
> *number_of_germinated seed1 is an indirect influence on*
> *number_of_established plant1*
> *number_of_plant1 is an indirect influence on number_of_dead1*
> *number_of_established1 plant is an indirect influence on growth_rate1*
> *number_of_dead is an indirect influence on growth_rate1*

This question is answered by taking the indirect influences found in the VIEW STRUCTURE and the PROCESS STRUCTURE.

7.6 Intrastate and interstate analyses

Intrastate analysis is the analysis of the causal structure of the system (see Chapter 4, section 4.2). Therefore it explains how changes start and propagate through the system. The intrastate analysis takes the view and process structure, and explains what the direct and indirect active influences are. These topics are examined in this section. A worked example is presented at the end of this section.

7.6.1 Intrastate analysis

The topic INTRASTATE ANALYSIS takes information about the initial causes of change (represented in the topic DIRECT INFLUENCES) and how the changes propagate (represented by the topic INDIRECT INFLUENCES) from the topic STATE DESCRIPTION:

```
                         intrastate analysis
                                  |
                 ---------------------------------------
                 |                |                    |
      state description    direct influences    indirect influences
```

```
----------------------------------------------------
INTRASTATE ANALYSIS:
        the current state of the simulation is described in STATE DESCRIPTION
        initial causes of change in current state are DIRECT INFLUENCES
        these changes can propagate within the state through INDIRECT INFLUENCES
----------------------------------------------------
```

7.6.2 Direct influences

The topic DIRECT INFLUENCES refers to the effects of active processes. Therefore, it explains the initial causes of change in the system. Explanations about the direct influences require references to the direct influence resolution (see Chapter 4, section 4.3). The final component of this topic is the calculation of the derivative of the directly influenced quantities[34].

```
                          direct influences
                                  |
        ------------------------------------------------------
        |                         |                          |
state description      direct inf resolution       calculated derivatives
```

[34] Calculation of directly and indirectly influenced quantities depends on the application of termination rules. Although these rules are important for explanations, they are not included in this thesis.

DIRECT INFLUENCES:

the current state of the simulation is described in STATE DESCRIPTION
direct influences are combined in DIRECT INFLUENCE RESOLUTION
derivatives of direct influenced quantity are CALCULATED DERIVATIVES

7.6.3 Direct influence resolution

In order to explain how direct influences are computed, the topic DIRECT INFLUENCE RESOLUTION refers to topics that describe positive and negative effects of processes, and current values of the quantities. The result is expressed in a topic (DIRECT INFLUENCE RESULTANT) that represents the combined effect of all active processes:

```
                    direct influence resolution
                                 |
          -----------------------------------------------------
          |             |              |                  |
     pos dir inf   neg dir inf    qtty values     dir inf resultant
```

DIRECT INFLUENCE RESOLUTION:

positive influences of processes are POS DIRECT INFLUENCES
negative influences of processes are NEG DIRECT INFLUENCES
current values of the quantities is QUANTITY VALUES
the combined effects of direct influences is DIRECT INFLUENCE RESULTANT

7.6.4 Calculated derivatives

The topic CALCULATED DERIVATIVES uses the direct influence resultant explained above to show how derivatives of directly influenced quantities are updated. This last topic (UPDATED QUANTITY VALUES) consists of the topic QUANTITY VALUES, modified by the effects of direct influences.

```
                     calculated derivatives
                               |
              ----------------------------------------
              |                                      |
   direct influence resultant              updated qtty values
```

CALCULATED DERIVATIVES
the combined effects of direct influences is DIRECT INFLUENCE RESULTANT
updated values of the quantities is UPDATED QUANTITY VALUES

7.6.5 Indirect influences

The topic INDIRECT INFLUENCES is similar to the direct influences topic. Proportionalities are also combined in a resultant, and this resultant is used to explain how new values are assigned to the derivatives of indirectly influenced quantities.

```
                            indirect influences
                                    |
         --------------------------------------------------------------
         |                          |                                 |
   state description       indirect inf resolution          assigned derivatives
```

INDIRECT INFLUENCES:
the current state of the simulation is described in STATE DESCRIPTION
the indirect influences are combined in INDIRECT INFLUENCE RESOLUTION
derivatives of indirect influenced quantities are ASSIGNED DERIVATIVES

7.6.6 Indirect influence resolution

The topic INDIRECT INFLUENCE RESOLUTION contains knowledge about positive and negative proportionalities, and takes into account the current values of the influencing quantities, determines a resultant that expresses the combined effects of the indirect influences.

```
                         indirect influence resolution
                                      |
                 --------------------------------------------------
                 |              |              |              |
            pos proport    neg proport    qtty values    indir inf resultant
```

INDIRECT INFLUENCE RESOLUTION:

the positive influences of processes are POS PROPORTIONALITIES
the negative influences of processes are NEG PROPORTIONALITIES
current values of the quantities is QUANTITY VALUES
the combined effects of indirect influences are INDIRECT INFLUENCE RESULTANT

7.6.7 Assigned derivatives

ASSIGNED DERIVATIVES is the topic for explaining how the values of the derivatives of indirect influenced quantities change. To update the quantity values, this topic takes into account the resultant of positive and negative indirect influences.

```
                         assigned derivatives
                                  |
                  ------------------------------------
                  |                                  |
       indirect influence resultant          updated qtty values
```

ASSIGNED DERIVATIVES

the combined effects of indirect influences are INDIRECT INFLUENCE RESULTANT
updated values of the quantities are UPDATED QUANTITY VALUES

The first state in the simulation about succession in the cerrado can be used as an example of the intrastate analysis. The graphical representation of the causal structure of the system (Chapter 6, Figure 6.5) shows that human actions are direct influences on fire frequency, and changes in this quantity propagate to other quantities through indirect influences (proportionalities).

The explanation is based on the topic INTRASTATE ANALYSIS. It starts with the direct influences from human actions (DIRECT INFLUENCES) and then includes the propagation of changes within the state (INDIRECT INFLUENCES). The explanation may be given in terms of values of derivatives, and may be something like:

Human actions cause fire frequency to decrease.

When fire frequency is decreasing, the amount of litter increases.

The increase in litter increases the moisture.

The increase in litter increases the amount of nutrient.

The increase in litter decreases the temperature.

The increase in litter decreases the amount of light.

The decrease in light decreases the number of born1 (grass).

(...)

This is a simplified example (see more details in section 7.9). There is only one direct influence on fire frequency, from human actions. The calculated derivative in this case is negative, and the quantity fire frequency decreases. The other utterances are based on the topic INDIRECT INFLUENCES applied to each quantity. Note that the number of causal links may increase easily: moisture, nutrient, and temperature are also indirect influences on the number of plants being born and dying. Finally, in this example there are no ambiguities. When ambiguities do occur, the simulation follows alternative values, and the explanatory facility needs to keep track of the possible outcomes.

7.6.8 The interstate analysis

As mentioned in section 7.5, behaviour is a sequence of states. In order to explain behaviour, it is necessary to compare the current state with the previous state and with future states. Comparison with the previous state is a type of explanation called postdiction (explanation about how the current state came about, given the situation described in the previous state). Given the current conditions, it may be possible to make predictions about what the next state will be.

```
                    interstate analysis
                            |
               ------------------------------
               |                            |
      behaviour prediction        behaviour postdiction
```

```
-----------------------------------------------------
INTERSTATE ANALYSIS:
        current state of the simulation is state STATE IDENTIFICATION
        current state came from previous state because of BEHAVIOUR POSTDICTION
        current state changes to the next state because of BEHAVIOUR PREDICTION
-----------------------------------------------------
```

7.6.9 Behaviour postdiction

BEHAVIOUR POSTDICTION requires the identification of the current and the previous state, and intrastate analysis in the previous state. In particular, the givens in the previous state must be compared with the conditions for the current state to hold. These topics are organised as follows:

```
                    behaviour postdiction
                              |
                 ---------------------------------
                 |                               |
         state identification            intrastate analysis
```

```
--------------------------------------------------
BEHAVIOUR POSTDICTION:
        current state of the simulation is state STATE IDENTIFICATION
        previous state changed because of INTRASTATE ANALYSIS
--------------------------------------------------
```

7.6.10 Behaviour prediction

BEHAVIOUR PREDICTION requires the identification of the current and the future state. As described in the behaviour postdiction, the intrastate analysis must focus on the givens of the current state. The effects of change should match with the conditions for the next state to hold. Although the topics involved in BEHAVIOUR PREDICTION are the same as those involved in behaviour postdiction, the states involved are different

```
                    behaviour prediction
                              |
                 ---------------------------------
                 |                               |
         state identification            intrastate analysis
```

```
--------------------------------------------------
BEHAVIOUR PREDICTION:
        current state of the simulation is state STATE IDENTIFICATION
        state will change because of INTRASTATE ANALYSIS
--------------------------------------------------
```

7.6.11 A worked example

In this section an example of interstate analysis is presented[35]. This example is taken from the simulation of the succession of cerrado communities shown in Chapter 6 (section 6.3). The focus is on the transition between Campo Limpo (state 2) and Campo Sujo (state 3). These two states are compared with respect to the behaviour of the population of trees. This is an interesting example, because in Campo Limpo there are no trees, whereas they are present in Campo Sujo. Therefore there is a change in the physical structure of the system, and new quantities and relations are added to the system. From the explanatory point of view, these changes reflect the conceptual structure of the system represented in the model.

The ecological knowledge involved in this situation refers to the effects of colonisation. Initially there are no individuals of a particular species (e.g. trees) in the area. However, there are some individuals (seeds) immigrating from other places, a process called *Colonisation*. The result is that a new population will establish in the area. Once there is a population (that is, the number of plants is greater than zero), then the basic processes (*Natality*, *Mortality*, *Immigration* and *Emigration*) become active and the population may start to increase.

States 2 and 3 can be compared as follows:

1) What are the main concepts used to describe states 2 and 3?

This question may lead to an answer such as:

In state 2 the situation can be described by the view structure:

no_population(population1)

---

[35] See footnote number 26.

The situation changes because of the processes described by the process structure:

colonisation_process(population1)

As a consequence, in state 3 the view structure becomes:

existing(population1)
plant_population(population1)
low_size_population(population1)
steady_population(population1)

and the process structure consists of the processes:

natality_process(population1)
mortality_process(population1)
immigration_process(population1)
emigration_process(population1)
general_population_growth_process(population1)

2) What dependencies and inequalities between quantities changed?

The conditions for the state 2 to hold are the following inequalities:

number of1 is equal zero
immigrated1 is greater than zero

The givens introduced in state 2 are the following causal influences:

number_of1 is directly and positively influenced by immigrated1

and the following inequalities:

the derivative of number_of1 is greater than zero

The conditions for the state 3 to hold are the following inequalities:

the number_of1 is greater than zero
born1 is greater than zero
immigrated1 is greater than zero
dead1 is greater than zero
emigrated1 is greater than zero
inflow1 is greater than outflow1

The givens introduced in state 3 are the following causal relations:

number_of1 is directly and positively influenced by growth_rate1
number_of1 is directly and positively influenced by born1

number_of1 is directly and positively influenced by immigrated1
number_of1 is directly and negatively influenced by dead1
number_of1 is directly and negatively influenced by emigrated1

and the following inequalities:

the derivative of number_of1 is equal to zero

3) What quantities changed their values from state 2 to state 3? What quantities retain the same value?

In state 2

the magnitude of number_of1 is zero
the derivative of number_of1 is plus

the magnitude of immigrated1 is plus
the derivative of immigrated1 is plus

In state 3

the magnitude of number_of1 is low
the derivative of number_of1 is zero

the magnitude of immigrated1 is plus
the derivative of immigrated1 is plus

the magnitude of number_of1 has changed
the magnitude and the derivative of immigrated1 have remained the same

7.7 Question types and candidate topics

In this section, the typology of questions developed in section 7.2 is associated with the topics of the didactic discourse identified in sections 7.4 - 7.6. A set of examples covering the most common questions expected during an interaction with the learning environment is presented.

Elaboration

Most of the elaboration questions refer to descriptions of the model elements. The following table summarises possible questions and the candidate topics for them.

Example question	Candidate topics
What is.... ?	OBJECT, MAIN CONCEPT, STATE DESCRIPTION
What is the (instantiated) name of ....?	OBJECT, QUANTITIES
What are the parts of X.? What are the attributes of X? What are the quantities related to object X?	OBJECT
What are the possible values of quantity Q? What is the value of Q in state N?	QUANTITIES, QUANTITY VALUES, MAGNITUDE VALUES, DERIVATIVE VALUES
What are the relations between quantity Q1 and quantity Q2?	QUANTITY RELATIONS
What are the quantities equal / greater than / equal or greater than / smaller / equal or smaller than Q?	INEQUALITIES
What are the direct influences on quantity Q?	POS DIRECT INFLUENCE, NEG DIRECT INFLUENCE
What are the indirect influences on quantity Q?	POS PROPORTIONALITY, NEG PROPORTIONALITY
What are the corresponding values to value V of the quantity Q?	VALUE CORRESPONDENCES, QUANTITY SPACE CORRESPONDENCES
What are the constraints between the quantities {Q1, Q2, ...} in order to calculate the value of Q?	QUALITATIVE EQUATION
What are the conditions for view V1 or process P1 to become active?	MAIN CONCEPT, CONDITIONS
What are the effects of view V1 or process P1 being active?	MAIN CONCEPT, GIVENS
How can state N be described?	STATE DESCRIPTION
What is the origin of state N? Which states follow from state N?	STATE IDENTIFICATION
What is the initial scenario in the simulation?	INITIAL SCENARIO
What are the main concepts used to describe the state N?	VIEW STRUCTURE, PROCESS STRUCTURE
What is the situation in state N?	VIEW STRUCTURE
What are the active processes in state N?	PROCESS STRUCTURE
What are the active direct influences in state N?	DIRECT INFLUENCES
What are the calculated values of the derivatives of quantities {Q1, Q2, ...}?	CALCULATED DERIVATIVES
What are the combined effects of active processes in state N?	DIRECT INFLUENCE RESULTANT
What are the combined effects of indirect influences on quantities {Q1, Q2, ...}?	INDIRECT INFLUENCE RESULTANT
How does influence X propagate within this state?	INTRASTATE ANALYSIS
What forces caused state N to appear?	BEHAVIOUR POSTDICTION
What are the effects of the current state on the system's behaviour?	BEHAVIOUR PREDICTION
How does a particular quantity change over states?	BEHAVIOUR EXPLANATION
Describe the behaviour of the system....	BEHAVIOUR EXPLANATION

Comparison

A particular type of Elaboration question refers to comparisons. In this case, two topics of the same type are required. The answer may refer to similarities and/or differences.

Example question	**Candidate topics**
Compare objects X1 and X2	OBJECTS
Compare quantities Q1 and Q2	QUANTITIES
Compare the values of quantities Q1 and Q2	QUANTITY VALUES
Compare the relations involving quantities Q1 and Q2	QUANTITY RELATIONS
Compare influences on quantity Q1 and Q2	POS DIRECT INFLUENCES, NEG DIRECT INFLUENCES, POS PROPORTIONALITY, NEG PROPORTIONALITY
Compare view S1 and view S2 Compare process P1 and process P2	MAIN CONCEPT
Compare state N1 and state N2	STATE DESCRIPTION
Compare initial scenarios ISl and IS2	INITIAL SCENARIO
Compare simulation S1 and S2	BEHAVIOUR EXPLANATION

Evaluation

Evaluation questions explore the relations between the quantities, in particular the causal influences:

Example question	**Candidate topics**
Why has the value of the quantity ... changed (increased, decreased)?	DIRECT INFLUENCES, INDIRECT INFLUENCES
Why does quantity ... have value ....?	QUANTITY RELATIONS, QUALITATIVE EQUATION
Why is the main concept (view, process)... applicable?	MAIN CONCEPT, CONDITIONS
Why did state... appear?	INTERSTATE ANALYSIS, BEHAVIOUR POSTDICTION

Exploration

These are the most general questions presented here. Answers to them will require references to almost all the topics mentioned in this chapter.

Example question	**Candidate topics**
What will happen if the initial scenario of the simulation is...?	INITIAL SCENARIO, BEHAVIOUR EXPLANATION
What will happen if the object... is introduced in the simulation?	INITIAL SCENARIO, BEHAVIOUR EXPLANATION
What will happen if the value of quantity... is .... within this particular state?	CAUSAL RELATIONS, BEHAVIOUR PREDICTION

7.8 Answering questions in a different domain

Are these topics and implemented routines for answering questions applicable to different domains? Given that the material presented here is based on the data structures and on the problem solving methods used in GARP for prediction of behaviour, in principle the topics and the question answering routines are domain-independent. Therefore they should be useful for any model developed in GARP.

To test this point, the representation for the topics and the explanation generator was used to explain aspects of a simulation using one of the balance models described in Bredeweg (1992)[36]. Bredeweg developed a series of models involving a balance and two containers filled with water and placed on each arm of the balance. Simulations with these models aim to predict the balance's behaviour when water is flowing out of the containers. These models were used to investigate the reasoning steps that a student is supposed to take when qualitatively predicting the behaviour of the system (see, for example, de Koning *et al.*, 1996).

The rationale behind this physical system may be expressed as follows: the two containers differ in width and height, but have the same weight when they are empty.

[36] See footnote number 26.

They differ also in the amount of contained water, and there is an outlet through which water flows in each container. The rate at which the water flows out (the flow rate) may also be different (although the outlets are equal), depending on the pressure at the bottom of each container. Pressure in turn may be captured by knowledge about the height of the water column. Therefore, depending on the difference in the mass of water contained in the containers, one balance arm may be heavier than the other and the balance may change its position. Eventually, when the two containers become empty, the balance will have reached the position of equilibrium.

The routines for describing states are used here to explain state 3. The resulting explanation may be something like the following:

1) What are the objects involved in state 3?

there is an object called balance1
which is an instance of balance

there is an object called container1
which is an instance of container

there is an object called container2
which is an instance of container

balance1 has left_arm with container1
balance1 has right_arm with container2

2) What are the quantities related to these objects?

container1 has_quantity amount_of_water1
it is a quantity type continuous
and has Quantity Space {zero, plus}

container1 has_quantity height_of_column1
container1 has_quantity width1

container2 has_quantity amount_of_water2
container2 has_quantity height_of_column 2
container2 has_quantity width2

balance1 has_quantity position1
it is a quantity type continuous
and has Quantity Space {minus, zero, plus}

balance1 has_quantity difference_in_weight1
it is a quantity type continuous
and has Quantity Space {minus, zero, plus}

3) What are the values of these quantities in state 3?

width1 has magnitude plus, derivative zero
amount_of_water1 has magnitude plus, derivative minus
height_of_column1 has magnitude plus, derivative minus

width2 has magnitude plus, derivative zero
amount_of_water2 has magnitude plus, derivative minus
height_of_column2 has magnitude plus, derivative minus

difference_in_weight1 has magnitude zero, derivative undefined
position1 has magnitude plus, derivative zero

4) What quantity relations hold in state 3?

width2 is greater than width1
the derivative of width1 is equal zero
the derivative of width2 is equal zero

height_of_column1 is a negative and direct influence on amount_of_water1
amount_of_water1 is a positive and indirect influence on height1

the Quantity Space of amount_of_water1 corresponds to Quantity Space of height_of_column1

height_of_column2 is a negative and direct influence on amount_of_water2
amount_of_water2 is a positive and indirect influence on height2

the Quantity Space of amount_of_water2 corresponds to Quantity Space of height_of_column2

height_of_column1 equals height_of_column2
amount_of_water2 is greater than amount_of_water1

position1 is directly and positively influenced by difference_in_weight1

5) How can the situation in state 3 be described?

balance_with_left_arm_up_right_down

6) What are the active processes in state 3?

change_in_mass_container1

change_in_mass_container2
change_in_position_from_equilibrium

7) How do changes start and propagate in state 3?

height_of_column1 is a negative and direct influence on amount_of_water1
height_of_column1 has magnitude plus
then value amount_of_water1 decreases

amount_of_water1 is a positive and indirect influence on height_of_column1
decreasing value of amount_of_water1 causes height_of_column1 to decrease

height_of_column2 is a negative and direct influence on amount_of_water2
height_of_column2 has magnitude plus
then value amount_of_water2 decreases

amount_of_water2 is a positive and indirect influence on height_of_column2
decreasing value of amount_of_water2 causes height_of_column2 to decrease

7.9 Planning the explanation

Having classified the question types and defined a set of topics that represent the domain knowledge, the next step is to plan the interaction that is aimed at getting the required information across to the user.

This planning process is done by the *Didactic Discourse Planner* (DDP) (see Winkels, 1992, for details). Basically DDP takes the information needed ('local need') with the knowledge to be conveyed to the student, and first looks in a library of skeletal discourse strategies to see if one of those is applicable to the current situation. If it is, it is instantiated to the current situation, and the strategy will be transformed to natural language and presented to the student. If none can be found, general fall back strategies will be refined to deal with the situation. The strategies take care of skipping or summarising information, possibly extending parts, sequencing it, minimising shifts of focus, etc.. They also take care of the linearisation of the discourse, for example, first referring to the cause of the explanation and then introducing new knowledge.

A general strategy in DDP consists of top-level strategies that have a specific purpose, and a set of sub-strategies required for achieving that purpose. Some examples of the strategy used here for explaining the simulations are:

a) Context: this strategy prepares the student to understand the rest of the utterances in the explanation. It also prepares the student to receive new information.

b) Remind: this strategy is applied to recall concepts that must already be known to the student. It may refer to basic concepts (such as objects) or to quantities already mentioned.

c) Signalling: this strategy is an announcement that something important will be said. It is important to separate parts of the discourse such as old and new knowledge.

d) New information: this is perhaps the most important part of the interaction. Here the main topic of the local need is explained, based on assumptions about the knowledge the student has about the topic.

e) Explain: this is part of the strategy of linking knowledge that is part of the current topic of discourse with related topics. These may include specific concepts (such as quantity and causal dependencies) or the result of comparisons between concepts (focusing on similarities and differences).

f) Refer same: given the requirements of conciseness and objectivity, this strategy can be used to avoid repetitions.

g) Closing: this is to indicate the end of the interaction.

Originally DDP was designed to provide help for users of information processing systems. Therefore, the strategies and tactics implemented are related to the performance of tasks, for example, opening files and deleting lines. These strategies and the tactics for presenting the didactic discourse obviously have to be modified for the present context. This is part of ongoing work.

DDP strategies implement general principles for didactic discourse, of which the two most important ones are the 'given ==> new' and the 'conciseness and relevance' principles'.

a) The 'given ==> new' principle means that the explanation should always link new information to given, or 'known' information. Practically, this means linking new information to something that the student already knows (Student Model), something that has been taught recently (Coaching History), something that has just been mentioned (Discourse Model), or something that just happened (Performance History).

b) the 'conciseness and relevance' principle means that the explanation should be to the point, and should not explain things the student already knows (or is supposed to know), should not introduce new topics, unless necessary for understanding the new information, and whenever possible should use references to existing information ('given') instead of describing a topic again. An interesting situation arises when explaining a topic when a similar topic is known, or has just been described. In this case, the focus is on the differences.

An example of the whole process of formulating a question, selecting relevant topics and planning the discourse can be given at this point. Given the simulation about the cerrado succession (Chapter 6, section 6.3), a question concerning the propagation of change of the decreasing fire frequency may involve the topicalization process described in section 7.3. The result is combined in the top-level topic INTRASTATE ANALYSIS. This may result in an explanation with the following structure:

[context]
[remind basic concept]

You know: there is a cerrado referred to as cerrado1

[remind quantity]

You know: cerrado1 has a quantity fire frequency referred to as fire frequency1.
It currently has the value plus and is decreasing.

[new information]
[explain causal dependency]

The decrease in fire frequency1 increases litter1.

[explain quantity]

litter1 is the quantity litter of cerrado1.
It currently has the value plus and is increasing.

[signalling]

The increase in litter1 has four effects:

[explain causal dependency]

1. The increase in litter1 increases humidity1

[explain causal dependency]

2. The increase in litter1 increases the nutrient1

[explain causal dependency]

3. the increase in litter1 decreases the light1

[explain causal dependency]

the decrease in light1 decreases the born3

[explain quantity]

born3 is the quantity born of grass1
It currently has the value plus and is decreasing.

[explain causal dependency]

The decreasing amount of born3 decreases the number_of3

[explain quantity]

number_of3 is the quantity number-of of grass1.
It currently has the value maximum and is stable.

[explain causal dependency]

The decrease in light1 increases the dead3

[explain causal dependency]

The increasing amount of dead3 decreases the number_of3

[explain causal dependency]
[explain similar]

4. The increase in litter1 decreases the temperature1

[refer same]

This propagates the same way as light1

[explain difference]

but now, for nutrient1 (...)

7.9 Conclusions

This chapter describes the use of qualitative models for supporting xplanations. Two types of explanation have been recognised in the literature. One is based on tracing the operations performed by the computer system. This is a useful type of explanation in the context of simulations, because it provides an account for the value calculation over the states. The second type of explanation draws on concepts that constitute the domain knowledge. Given that objects, situations, processes and conditions for things to happen are explicitly represented in qualitative models, the conceptual structure of the system can be used for explanations. The result is that simulation models can also be explanation models.

One way of accessing the concepts represented in the models is to transform the modelling primitives into topics of the didactic discourse. This is an approach of proven effectiveness, not only for representing basic concepts but also for building representations of more complex concepts such as 'state' and 'behaviour'.

Automatic generation of explanations requires mechanisms for selecting what to say and how to say it. A solution for the former is to have topics attached to questions type, whereas the latter can be accomplished by using strategies and tactics for planning the discourse. This approach has the potential for tailoring explanations according to the student's needs. This is point to be expanded in future work.

It has been shown in this chapter that both the organisation of the topics and the mechanisms for explanation generation can be domain independent. This is an important feature for the development of flexible educational tools.

Finally, the work described in this chapter shows the potential for combining qualitative simulations and natural language explanations in learning environments. Promising extentions for this work is in associating qualitative models with different presentations of the domain knowledge, such as graphics, animations or multimedia applications.

Chapter 8. Discussion and concluding remarks

The main goal of the work described in this thesis is the development of modelling approaches for building qualitative models about ecology to be used in educational contexts. In this final chapter, a brief discussion on the main themes explored in this thesis - ecological modelling, qualitative reasoning and learning - is presented.

8.1 About ecological modelling ...

The first contribution of this work is related to the characterisation of the notion of 'qualitative knowledge'. A substantial amount of ecological knowledge is expressed in qualitative terms. However, under this label there is a mixture of different types of knowledge. This thesis is concerned with qualitative representations of quantitative knowledge.

It has been shown that qualitative knowledge about quantities in turn may refer to magnitudes and derivatives. Each has its own characteristics and can be used for different purposes. Magnitudes are relevant information for describing the system during each state. They allow for comparisons between quantities, and support inferences about the conditions for ecological phenomena to happen. Derivatives, on the other hand, are useful for expressing knowledge about the dynamics of the system. They provide information about the behaviour of the quantities, and support predictions about future states of the system.

This thesis discusses how these two types of knowledge may be manipulated by qualitative reasoning techniques. Reasoning with magnitudes requires the use of some sort of qualitative mathematics for establishing relations between quantities and calculating values. The minimum requirement for using knowledge about the derivatives is a method for analysing the rate of change of quantities.

The studies developed here show that these techniques are useful for representing this knowledge in a formalised way, so that it can be used in simulations and in explanations.

The models presented in this thesis are fairly simple models, compared with real-world ecological problems and indeed with many quantitative simulation models of similar systems. The more complex model described here, about the succession in cerrado (Chapter 6), involves 33 variables. This is not small for a purely qualitative model, but is still far from representing the complexity of ecological systems. However, the modelling approach presented here has the potential for dealing with larger models.

Some important elements in ecological knowledge were not addressed in this thesis, and may be topics for future research. Among them, it is worth mentioning non-causal relations between quantities, reasoning involving higher-order derivatives, and temporal reasoning about ecological systems.

When we say, for example that 'high trees have large trunks', we are establishing a correlation between two quantities that are not causally related. This is particularly useful in sciences such as ecology, in which there are no first principles to support generalisations, and research still is looking for possible relations between the characteristics of ecological systems. The ontology selected for this work, QPT, is not appropriate for tackling this sort of problem, but the component and constraint-based approaches may be helpful (see Chapter 2).

Another problem which was not explored here involves reasoning with second or higher order derivatives. For example, when we say 'the population is increasing slower than it was in the beginning of the simulation' we are taking into account the magnitude of the derivative of the quantity. This type of reasoning is required, for example, in the Lotka-Volterra model of density-dependent populations, one of the first population models presented in any textbook of ecology. This is a typical situation in which qualitative models are useful, because the most interesting features about the behaviour of the population can be shown without using complex mathematical reasoning. For example, Kamps & Péli (1995) present a qualitative model of the Lotka-Volterra equation (implemented in GARP).

Rickel & Porter (1997) used time scale information as a mechanism when selecting relevant influences for answering prediction questions. However, ecological systems frequently involve cyclic phenomena, and interactions between processes occurring at different organisational levels (see Mota *et al.*, 1996). These aspects require some form of temporal reasoning systems, but this was not addressed in this thesis because of the complexity of the theme. However, it certainly should be included in educational models.

The research described in this thesis focused on the potential of qualitative models for ecological education. However, qualitative modelling may be useful as a complement to quantitative modelling in ecological research. As described in Haefner (1996), building mathematical models starts with the conversion of an objective statement, and a set of hypotheses and assumptions into an informal, conceptual model. This is useful for identifying the necessary modelling components and the relations between them, and is often done in qualitative or diagrammatic terms. The next step is the mathematical formulation of the model. For many beginners, this is the most difficult stage. As discussed in Chapter 2, there are many similarities between modelling with differential equations and modelling according to the main QR formalisms. Therefore qualitative models may provide an useful intermediate step between the conceptualisation of the model and its mathematical implementation. Also qualitative simulations may be used as part of the process of checking the correctness of the quantitative model.

8.2 ... qualitative reasoning ...

Beside the contribution to ecological modelling, this thesis presents also a contribution to research in qualitative reasoning. Few studies in QR thus far have addressed the problem of using theories and techniques developed for physics and engineering in different domains, and of comparing different techniques for modelling the same problem (see one example in Bonissone *et al.*, 1985). Virtually none have done across different domains. Here the comparison considers the possibility of representing different kinds of ecological knowledge for educational purposes. In particular, the formalisms were evaluated in terms of the vocabulary used for describing the system, representations of the causal relations and general aspects of the simulation.

The selection of QPT as the main ontology, combined with SIMAO (see Chapter 2) proved to be successful. The conceptualisation of the system in terms of objects that interact via processes is very close to a common-sense view. The vocabulary provided by QPT (objects, conditions, views, processes) allows for descriptions of the most important elements involved in reasoning about quantities in ecological systems. Derivatives may easily be represented in QPT, whereas magnitudes are better handled in SIMAO. It has been shown that the latter may provide a representation for constraints lacking in the former.

QPT is not a good option for representing phenomena in which no processes are involved. For example, transporting things from one part of the environment to others is a kind of problem that could not be represented within this framework (as in Plant & Loomis, 1991). This was not the case for the problems modelled in this thesis.

SIMAO's algebra provides a set of operators and laws necessary for calculating the magnitudes of the quantities and gives an indication of how proportionalities may be converted into qualitative equations. However, two points limit this approach. Firstly, there are no algebraic operations involving the zero and negative values (although it is possible to include zero in the quantity space without using it in calculations, as for example, in Hunt & Cooke, 1994). Secondly, the combination of qualitative values itself has understandable limitations. For example, the operation of adding equal values will always produce the same value (such as {p+p+p+p = p}).

From this perspective, the comparison between models built within the System Dynamics and SIMAO frameworks, presented in Chapter 5, has to be analysed carefully. These results indicated that the results of the latter were comparable to the output of the former. However, the simulations ran over only one time step, and nothing can be said about the predictions generated by both models over longer periods of time because the results obtained with the two models diverge very much. An appropriate approach to this matter may require better definitions for the correspondences between qualitative and quantitative values, and some statistical analysis. This is beyond the scope of this thesis.

GARP was very useful for the implementation of the models described in this thesis for two reasons. Firstly, GARP's data structure was used for representing the knowledge in the models discussed in Chapter 5. Although these models were not implemented in GARP, the representation of views and processes was done in the same way. Secondly, the models described in Chapter 6 were actually implemented in GARP. The decision for using the same data structure was based on practical reasons: it was possible to use the same explanation generator (see Chapter 7) for all the models described in this thesis.

GARP is a flexible qualitative simulator, which has been used in a number of education-related research (see, for example, Koning et al, 1997a: 1997b). No changes in GARP's architecture or set of rules were required for implementing models in ecology, apart from those introduced to control the simulation (see Chapter 6). This is an indication of the generality of the unified approach proposed by Bredeweg (1992). Recently the idea of a common language for building qualitative models has re-emerged (Bobrow *et al.*, 1996), as a follow up to Crawford *et al.* (1990) and Bredeweg's pioneering initiative.

A point to note in this comparison between building qualitative models in ecology and in physics or engineering is concerned with the selection of possible values for the quantities. In physics the quantity spaces are divided in points and intervals. Points define relevant changes into the system, such as changes of state (boiling, freezing, melting). Forbus & de Kleer (1993) say that "this is an example of the *relevance principle* of qualitative physics: a representation must be capable of making relevant distinctions. Simple representations of value like 'tepid, warm, hot, very-hot, etc.' tend not to have this property. Does water boil when it is hot, very -hot etc.? Only if we pin these labels down by defining them in terms of a physically meaningful comparison (ex., the boiling point) can we make more interesting predictions."

There are few similar examples in ecology. The point zero is an obvious example of a point that makes relevant distinctions: it defines the absence of something. In population ecology the value K (carrying capacity) defines the number of individuals of a stabilised population. However, in most of the cases such significant points cannot be determined. The work described here suggests that in ecology the problem is not in defining points but in using a combination of factors to define relevant ecological changes. For example, see the definitions of cerrado communities in Chapter 6.

This thesis presents also a contribution for 'modelling the modelling process' (Muetzelfeldt, 1991). In fact, this is a common goal for both ecological modellers and the QR communities. The guidelines presented in Chapter 4, which were followed during the implementation of the models described in Chapters 5 and 6 summarise the main points. For example, the 'one concept, one model fragment' rule, which proved to be a useful tool for organising the knowledge to be encoded in the library.

The advantages of the modular approach taken in this thesis were already discussed in Muetzelfeldt (1995): (a) simplification of the task of designing, implementing and modifying models; (b) increased co-operation between modellers and non-modellers; (c) increased reusability; (d) supporting for the modelling process; (e) increased clarity of communication of model structure; and (f) the ability to investigate model components separately. These points are applicable to the models described in this thesis.

The research described here may be extended in several directions, but of particular interest is the development of tools for supporting non-modellers. Ecologists and teachers should be able to develop their own models, according to their own needs, perhaps starting with a common library.

Related work is presented in Robertson *et al.* (1991). These authors are concerned with the development of mechanisms for helping ecologists to build mathematical models. The methodology developed here can be used for creating 'templates' (as suggested by Walker & Sinclair, 1995) for representations of ecological processes. As mentioned above, qualitative models built according to QPT and other formalisms (see Chapter 2) are similar to differential equation models in many respects. Therefore model fragments representing views and processes could be part of the interface in computer programs designed to create ecological simulation models automatically.

The framework proposed in Chapter 4 for building qualitative models to be used in education is another contribution to the formalization of the modelling process. Separating the structure of the system being modelled in terms of conceptual, causal and mathematical structures is a useful approach for two reasons. Firstly, it provides more clarity for the definition, classification, comparison, and evaluation of qualitative models. Secondly, it establishes a difference between *what is represented* and *how it can be used*. For example, the conceptual structure encodes knowledge about objects, situations and mechanisms of change, and is essential for explanations.

8.3 ... and learning environments

From the knowledge acquired about the cerrado vegetation (Chapter 3), a number of educational goals for the models developed in Chapters 5 and 6 were defined. The analysis of the models shows that these goals were achieved. The effects of fire on the basic processes of the populations (e.g. flowering, seed production, germination etc.), and in the succession of communities, could be represented and used to explain changes in these ecological factors. The level of detail is low, and should increase for actual use in the classroom. However, as discussed in Chapter 4, more details are in general associated with more complex simulations, with more ambiguities and branching in the envisionment graph. A possible solution is the use of model fragments that encode knowledge used for explanation but not for simulation ('inert' model fragments). This was not tried but there is nothing fundamentally wrong in it.

Ambiguity often appears in qualitative simulations. It has a role to play in education. In this thesis three approaches for handling ambiguities were presented:

a) Students are called on to solve the ambiguous situation (Chapter 5). The positive aspect of this approach is the development of their decision-making abilities. One negative point is the several interruptions during the simulation.

b) The modeller introduces annotations to influences about their strength (Chapter 5). This is good for the simulation to continue, but there is no added value for the learning process.

c) The simulator tries all the possible solutions and the envisionment graph branches (Chapter 6). This can be good for an overview of the possible behaviours of the system. The problem may be the excessive and irrelevant details in the simulation. The solution may be a combination of the three approaches, according to the educational goals to be achieved.

In educational interactions, qualitative models can be used for simulations involving different aspects of the curriculum. The models described in Chapter 6 were used in this way. Different initial scenarios produced simulations exploring different view points on the problem , and different sequences of simulation models were created. The result was a sequence with topics in increasing complexity (one population, two populations, communities). This approach points to the possibility of work related to the model progression implemented by White & Frederiksen (1990).

Bredeweg (1992), among others, showed that qualitative models support prediction of behaviour from the description of the structure of the system. A contribution of this thesis is to show that it is possible to derive explanation about the behaviour from the structure of the system. The potential for deriving explanations from qualitative models was recognised long ago (see, for example, Anderson, 1988). Causal explanations have been the most common output from this type of model. There is a number of techniques presented in Chapter 2 for this purpose: causal directed graphs (Guerrin, 1991); mythical causality (de Kleer & Brown, 1984); causal ordering (Vadillo *et al.*, 1997); influences and proportionalities (Forbus, 1984). This thesis presents a new contribution to this problem. Here, the modelling primitives used for building the models are also the primitives used for creating the explanatory discourse. A set of topics of the discourse were created exploring the concepts represented by these primitives, and a number of examples in Chapter 7 show the potential for this approach in explanation generation.

The contents of the explanation can be (at least partially) determined by the selection of these topics using a didactic discourse planner such as DDP (Winkels, 1992). However, several points related to the explanation contents were not addressed in this thesis. For example, answers to evaluation and exploration questions (Hartley *et al.* 1990) are more complex and requires the examination of the whole simulation. These are part of ongoing work.

Another important issue that was not addressed here refers to *how* to present the explanation to the students. A set of tactics and strategies implemented in Winkels' DDP can be used to control the explanatory interaction, and this is ongoing work. The integration of GARP and DDP in a learning environment is currently being implemented by Bredeweg, Winkels and the author. The models presented in Chapter 6 and the explanation generator outlined in Chapter 7 of this thesis are part of this work.

A natural extension of this research program is the inclusion of the work in cognitive diagnosis described by Koning *et al* (1997a; 1997b) to the explanation generator. The models and the topics of the explanatory discourse presented here may be used as handlers for the diagnoser. Since the modelling primitives are being used for explanation and for diagnosis, it is feasible to use the vocabulary used in the explanatory interaction (question - answer) for accessing the reasoning network and supporting diagnosis.

Scientific research has been considered the golden standard for education. However, this does not mean that scientific models should also be used in the classroom. The use of differential equation models for teaching population ecology is paradigmatic.

This is clearly an inefficient approach. The students are not able to use these models and find difficult to understand the domain using them. As mentioned above, there is a need for qualitative models such as those presented in this thesis in the classroom.

The work by Forbus & Gentner(1986) concerning canonical sequences in learning physical domains points to possible ways of organising the curriculum (see Chapter 2). Although these authors have recently changed their view (Forbus & Gentner, 1997) and claimed that the stages may be more tightly interwoven than they suspected, their original intuitions are still valuable. The sequence sounds appropriate to the author, based on his experience as a teacher and researcher in the ecology of the cerrado. Knowledge about general ecology and about the cerrado in particular, can be roughly classified according to these four stages: in the majority of subjects, we are in the two initial stages, protohistories and causal corpus. Most of common-sense and expert knowledge are naive models of the ecological systems, and there are very few expert (mathematical) models. The development of expert models should certainly continue to be the main goal of scientific research and higher education, but the development of Naive Ecology seems to be very important.

Carefully designed evaluations of these models and their importance in supporting simulations and explanations are necessary, in order to assess the actual value of using qualitative models and explanation facilities described in this thesis in the classroom. However, the potential for using qualitative models in education has been demonstrated.

Beside the potential of qualitative models for simulations and explanations, domain models can be very useful in educational contexts for different purposes. Some points are discussed below.

Domain models can provide handles for students to explore different aspects of the curriculum, from different points of view. This can be achieved with the models presented in this thesis is different ways. For example, by using different initial scenarios it is possible to involve the students in different problem solving activities, and therefore to achieve different educational goals.

It may also be possible to generate questions from the domain models, and use them to assess the student's knowledge in a particular issue. For example, queries referring to the calculation of the values of certain quantities can easily be implemented. The answers produced by the student can be compared to those produced by the learning environment.

Reasoning qualitatively about ecological systems is part of the everyday life of students, teachers and researchers. A lesson learned during the work described in this thesis is that students would benefit from reasoning qualitatively in a more formalised way, and that this type of reasoning can be object of training. For example, problems involving the magnitude of the quantities can be tackled with the techniques presented in Chapter 5, while problems involving derivatives require the approach taken in Chapter 6.

The modelling process is in itself a rich experience that can be explored in education. Modelling requires the understanding of the problems involved in a particular situation, the assessment of priorities and the ability for representing domain knowledge using a certain language. The development of tools for supporting the modelling process is a promising topic for future research.

The domain models developed here have shown the potential for supporting natural language explanations. However, learning environments are by no means restricted to texts. Multimedia applications are particularly interesting for ecological education, and could be associated with qualitative models. For example, the types of cerrado communities represented in the simulation of the succession in cerrado (Chapter 6) can easily be illustrated with images. The influence diagram can be inspected (and maybe changed) if the learning environment has a graphical interface.

In conclusion, this thesis showed the potential of QR techniques for ecological modelling, confirmed the generality of most of the techniques developed originally for physics and engineering, suggested some guidelines for the modelling process, and presented a promising approach for the generation of explanations in interactive learning environments.

More than 30 years ago, Anisio Teixeira, a Brazilian educationalist, predicted that the school in the future would be different: audio-visual resources of different types, students mastering the learning process, and teachers giving support to them. Education would be democratic and really able to promote changes (the changes required in the Brazilian society). These changes are on their way.

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Appendix

GARP's data structures

GARP was implemented in Prolog, as described in Bredeweg (1992). Knowledge in GARP is organised in five main modules: *isa*, *quantity space*, *rules*, *input_system* and *library*. Each encode part of the knowledge using a particular set of primitives. The data structures were used for representing knowledge in the implementation of the models described in Chapter 5 (*Life Cycle III - IV*). They are also the basis for the topics used in explanations described in Chapter 7. The most important primitives for the purposes of this thesis are described in this Appendix.

1) Isa hierarchy of objects

Describe the objects in the world. It has been extended to include (biological) entities, concepts and actions. It is based on the predicate isa/2. For example, the notion of *Miconia* is encoded below as an example of shrub, which is a type of plant, a biological entity among the existing entities in the model:

```
isa( entity, nil ).
isa( biological_entity, entity ).
isa( plant, biological_entity ).
isa( shrub, plant ).
isa(miconia, shrub).
```

2) Quantities

Quantities are represented in GARP as 'parameters', in the slot Parameters of termination rules, input systems and system structures. The general representation is the following:

parametername(InstanceName , Par_inst_Name , Type , QSpace) , where the functor is the name of the quantity in a predicate with four arguments: the first is the instance of the object to which the quantity is associated, an instance name for the quantity, the type of quantity (it could be a numerical quantity, but in the models described in this thesis is always qualitative) and the label for the quantity space. For example,

```
light( Cerrado, Light, _, p )
```

represents the quantity light which belongs to an instance of the cerrado. Its name in the current model is Light (instantiated, for example, as light1 in the simulation). It is a qualitative quantity and its quantity space is {plus}.

3) Quantity spaces

Encodes the knowledge about possible sets of values the quantities can assume. It is an important element to define the scope of the model. Alternative quantity spaces can be assigned to quantities, but not in the same model fragment. Therefore, alternative representations for the values of a quantity can coexist in the same library, as independent model fragments (see Chapter 6). The quantity space defined in the initial scenario (the input system) will be used to select appropriate model fragments during the simulation.

Quantity spaces consist of values expressed as points and intervals. In physics, this is an important distinction (for example, to represent a substance as a liquid (within an interval of values of temperature) with a boiling point (a point in the temperature scale of values)). Such distinction may be less important for the models about fire in the cerrado. For example, apart from the values of derivatives ({minus, zero, plus}), SIMAO's quantity spaces are defined only with intervals.

QS's are modelled by the predicate quantity_space / 3, in which the first argument is a label for the QS (e.g. zlmhm), the second is the parameter to which the QS is associated, and the third is a list of points and intervals. The example presented below includes the most used QS in the models described in Chapter 6 {zero, low, medium, high, maximum}.

```
quantity_space( zlmhm, X,
    [ point( zero ),
        low,
        point( medium( X ) ),
        high,
      point( max( X ) )
        ] ).
```

4) Quantity values

The values of the quantities are represented by the predicate value/4, in which the first argument is the name of the quantity in the current model, the second is the quantitative value (not used in this thesis), the third is the current value magnitude of the quantity, and the fourth is the current value of the derivative:

value(Par_inst_Name, _, Par_inst_Value, CurrentDerivative)

For example, at a certain point of the simulation, the instance light1 of the quantity Light (described above) has value 'plus' and is decreasing (derivative 'minus'):

```
value( light1, _, plus, minus )
```

5) Quantity relations

The relations between quantities used in GARP are the following:

Relations between magnitudes:

a) greater(Par1, Par2)

Value of the first quantity is bigger (larger) than the second.

b) greater_or_equal(Par1, Par2),

Value of the first quantity is bigger (larger) or equal to the second.

c) smaller(Par1, Par2),

Value of the first quantity is smaller than the second.

d) smaller_or_equal(Par1, Par2)

Value of the first quantity is smaller than or equal to the second.

e) equal(Par1, Par2)

Values of the two quantities are equal.

Relations between derivatives:

f) d_equal(Par1, Par2)

g) d_greater(Par1, Par2)

h) d_smaller(Par1, Par2)

These primitives represent relations between the values of the derivatives. They describe situations in which the derivatives of the first quantity is equal to, greater than of smaller than the derivative of the second quantity.

Correspondences:

i) v_correspondence(Par1, Val1, Par2, Val2)

correspondence between a particular value of one quantity with a particular value of the other quantity;

j) q_correspondence(Par1, Par2)

correspondence between all the values in the QS of both quantities:

Causal relations

k) prop_pos(Par1, Par2)

l) prop_neg(Par1, Par2)

Indirect influences (qualitative proportionalities). They indicate that the value of the derivative of the second quantity is assigned to the derivative of the first quantity.

m) inf_pos_by(Par1, Par2)

n) inf_neg_by(Par1, Par2)

Direct influences. They indicate that the magnitude of the second quantity sets the value of the derivative of the first quantity. They only appear in descriptions of processes and agent models (aggregated processes).

6) Rules

Rules are model fragments used to guide the transitions and terminations during the simulation. The majority of rules are domain independent, such as the example presented below. However they can be used by the knowledge engineer (or teacher) for the specification of details about the domain or about particular simulations.

Rules have two parts, conditions and givens. The former must be satisfied for the rule to be applied in a certain scenario. The latter indicates the changes caused to the system. They encode much of the knowledge also represented in the other model fragments (input system and system structure), using the same syntax.

A rule is modelled by the predicate rule/4 with the following arguments: the type of rule (continuity, termination), the name of the rule, the conditions for the rule to apply, and the effects of the rule being applied (the givens):

rule(TypeOfRule, NameRule, Conditions, Givens)

For example, suppose a quantity is increasing and goes from a point to the next higher interval in the quantity space. The conditions for this change to happen are: the value of the quantity 'Par' has current value 'Point' and derivative 'plus'. If the point meets the interval 'Interval' in the QS of that quantity 'Par', then, as a result, the quantity

'Par' takes the value 'Interval', and its derivative will be greater or equal to zero. This is encoded in the following rule:

```
rule( termination, [ to_interval_above( Par ) ],
    condition([
        par_values([
            value( Par, Q, Point, plus )
            ]),
        quantity_spaces([
            meets( Par, [ point( Point ), interval( Interval ) ] )
            ])
        ]),
    result([
        par_values([
            value( Par, Q, Interval, _ )
            ]),
        par_relations([
            d_greater_or_equal( Par, zero )
            ])
        ])
    ).
```

7) Input_system

Input systems are a kind of model fragment describing a particular configuration of the system at the beginning of the simulation. In GARP's terminology, an Input system is a System Model Description or SMD for the initial scenario. Each step of the simulation is described in a similar way, by other SMD. These SMD act as input systems for the following steps of the simulation. For details, see Bredeweg (1992).

The description of the initial scenario is one of the most important elements for the simulation. Input systems express the set of conditions for the simulation to start. They include information about the objects included in the model (instances of objects defined in the isa hierarchy), the quantities involved in the simulation, their initial values, and possible inequalities expressing initial relations.

An input system (or any other SMD) is represented by the predicate smd / 6 with the following arguments: the name of the input system, the objects or system elements, the quantities, their values, the relations that hold in this descriptions of the system, and other active model fragments.

```
smd( NameMFrag, System_elements, Parameters,
         Par_values, Par_relations, System_structures).
```

In the example given below, in the simulation started by the input system called 'a tree population and fire increasing', there is a population of trees in the cerrado, and an agent model (an aggregate of processes represented by their effect) called 'fire frequency increaser'. There are quantities of interest for this simulation related to the trees and to the cerrado ecosystem. The number of plants and the flows of the basic processes (natality, mortality, immigration and emigration) are related to tress. Some environmental factors of the cerrado, such as moisture, nutrients, light, temperature and the fire frequency in that area are related to the cerrado. Some of the initial values are declared, such as the 'high' number of trees, the values 'plus' for most of the environmental factors. Others, such as the values of the derivatives of all quantities and the fire frequency, are left open. The initial scenario also includes the restriction that there is no immigration and emigration.

```
smd( input_system( 'a tree population and fire increasing' ),
        system_elements([
          instance( Cerrado, cerrado ),
          instance( Population, population ),
          instance( Plant, tree ),
          has_attribute( Population, consists_of, Plant ),
          instance( Fire_increaser, fire_frequency_increaser )
            ]),
        parameters([
          number_of( Plant, Number_of, _, zlmhm ),
          born( Plant, Born, _, zp ),
          dead( Plant, Dead, _, zp ),
          immigrated( Plant, Immigrated, _, zp ),
          emigrated( Plant, Emigrated, _, zp ),

          moisture( Cerrado, Moisture, _, p ),
```

```
    nutrient( Cerrado, Nutrient, _, p ),
    light( Cerrado, Light, _, p ),
    soil_temperature( Cerrado, Soil_temperature, _, p ),
    fire_frequency( Cerrado, Fire_frequency, _, p )
      ]),
  par_values([
    value( Number_of, _, high, _ ),
    value( Born, _, plus, _ ),
    value( Dead, _, plus, _ ),

    value( Moisture, _, plus, _ ),
    value( Nutrient, _, plus, _ ),
    value( Light, _, plus, _ ),
    value( Soil_temperature, _, plus, _ ),

    value( Fire_frequency, _, _, _ )
      ]),
  par_relations([
      equal( Immigrated, zero ),
      equal( Emigrated, zero )
      ]),
  system_structures([
      ])
).
```

8) Library

The library consists of a collection of model fragments called 'system structures'. These modelling primitives are represented in a rule-like way, with a set of conditions for the fragment to be active, and the givens, that is, new knowledge introduced when the model fragment is active. Views and processes are modelled as system structures. Structured knowledge can be represented by using an isa hierarchy between model fragments. In Chapter 6, for example, isa hierarchies of processes and cerrado communities are presented.

System structures are implemented by the predicate system_structures/4, with arguments to represent the name of the model fragment, its links in the isa hierarchy of model fragments, the conditions for the fragment to become active, and the givens, that is, the consequences of that fragment being active.

system_structures(NameMFrag, Isa, Conditions, Givens)

The example given below describes the general ecosystem of cerrado, the cerrado sensu lato. It includes an instance of the cerrado communities and instances of trees, shrubs and grass. There are few conditions for this model fragment to apply: the existence of the objects and an explicit representation of the number of trees (with any value). When the fragment is active, the following quantities and relations are introduced in the model: litter, moisture, light, nutrient, soil temperature, cover and fire frequency. It is stated in this model fragment that cover has its value linked to the value of the quantity number of trees.

```
system_structures( cerrado_sensu_lato( (Grass, Shrub, Tree) ),
    isa([ composition_view ]),
    conditions([
        system_elements([
            instance( Cerrado, cerrado ),
            instance( Tree, tree ),
            has_attribute( Cerrado, consists_of, Tree ),
            instance( Shrub, shrub ),
            has_attribute( Cerrado, consists_of, Shrub ),
            instance( Grass, grass ),
            has_attribute( Cerrado, consists_of, Grass )
            ]),
        parameters([
            number_of( Tree, Number_of1, _, zlmhm )
            ]),
        par_values([
            ]),
        par_relations([
            ]),
        system_structures([
            ])
        ]),
    givens([
        system_elements([
            ]),
        parameters([
          litter( Cerrado, Litter, _, p ),
```

```
        moisture( Cerrado, Moisture, _, p ),
        light( Cerrado, Light, _, p ),
        nutrient( Cerrado, Nutrient, _, p ),
        soil_temperature( Cerrado, Soil_temperature, _, p ),
        cover( Cerrado, Cover, _, zlmhm ),
        fire_frequency( Cerrado, Fire_frequency, _, p )
          ]),
      par_values([
        value( Litter, _, plus, _ ),
        value( Moisture, _, plus, _ ),
        value( Light, _, plus, _ ),
        value( Soil_temperature, _, plus, _ ),
        value( Nutrient, _, plus, _ )
          ]),
      par_relations([
        dir_q_correspondence( Cover, Number_of1 ),

        prop_pos( Cover, Number_of1 ),
        prop_neg( Litter, Fire_frequency ),
        prop_pos( Litter, Cover ),
        prop_pos( Moisture, Litter ),
        prop_neg( Light, Litter ),
        prop_pos( Nutrient, Litter ),
        prop_neg( Soil_temperature, Litter )

          ]),
      system_structures([
          ])
      ])
  ).
```

Processes and agent models are represented in the same way. The only difference is the presence of direct influences in the slot par_relations of the givens. For example, consider the natality processes. When this process is active, it sets a positive direct influence on the number of individuals of a particular species:

```
system_structures( natality_process( Population ),
     Isa,
     Conditions,
     givens([
       system_elements([
```

```
        ]),
    parameters([
        number_of( Species, Number_of, _, zlmhm )
        ]),
    par_values([
        ]),
    par_relations([
        inf_pos_by( Number_of, Born )
        ]),
    system_structures([
        ])
    ])
).
```

Published papers

During the PhD course, the following papers describing the research presented in this thesis were presented in conferences:

1)
SALLES, P.S.B.A.; MUETZELFELDT, R.I. & PAIN, H. (1995) Qualitative Models in Ecology and their Use in Intelligent Tutoring Systems. In *Notes of the workshop 'The use of Qualitative Reasoning Techniques in Intelligent Learning Environments'*, at the World Conference on Artificial Intelligence and Education (AIED), Washington, August, 1995.

2)
SALLES, P.S.B.A.; MUETZELFELDT, R.I. & PAIN, H. (1996a) Qualitative Models in Ecology and their Use in Intelligent Tutoring Systems. In Iwasaki, Y. & Farquhar, A. (eds.) *Proceedings of 10th. International Workshop on Qualitative Reasoning (QR'96)*. AAAI Technical Report WS-96-01.

3)
SALLES, P.S.B.A.; PAIN, H. & MUETZELFELDT, R.I. (1996b) Qualitative Ecological Models for Tutoring Systems: a Comparative Study. In Brna, P. ; Paiva, A. & Self, J. (eds.) *Proceedings of the European Conference of Artificial Intelligence and Education,* Edições Colibri, Lisbon, Portugal.

4)
SALLES, P. & BREDEWEG, B. (1997) Building Qualitative Models in Ecology. In Ironi, L. (ed.) *Proceedings of the 11th. International Workshop on Qualitative Reasoning (QR'97)*. Instituto di Analisi Numerica C.N.R., Pubblicazioni no. 1036 , Pavia, Italy.

5)
SALLES, P.; BREDEWEG, B. & WINKELS, R. (1997) Deriving Explanations from Qualitative Models. In Boulay, B. & Mizoguchi, R. (eds.) *Artifical Intelligence in Education: Knowledge and Media in Learning Systems. Proceedings of AI-ED97 World Conference on Artificial Intelligence in Education*, Kobe, Japan. Amsterdam, IOS Press.

Copies of these papers are annexed to this thesis.

QUALITATIVE MODELS IN ECOLOGY AND THEIR USE IN INTELLIGENT TUTORING SYSTEMS

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Abstract

Qualitative reasoning can be very useful in ecological modelling given the qualitative nature of data about ecosystems. We are trying different approaches to model the vegetation dynamics of Brazilian cerrado. These qualitative models are being evaluated in order to assess their suitability as providing the domain knowledge in tutoring systems. Two formalisms we have explored are briefly compared here.

1. Motivation

Consider a scenario in which there is a large number of plants, the area has been burned recently, temperature is hot and soil is very dry. With these conditions, many biological processes can be inhibited, as for example, flowering, seed production and germination. Consequently, few flowers will be produced, there will be few seeds and many of them will fail to germinate. At the same time, some plants are going to die. Thus, population growth will be negative and the number of plants in the population in the next time unit is expected to be smaller.

If we want to model the situation described above, either to reason about it or to simulate the effect of changing environmental conditions, many problems will arise. Traditional approaches based on numerical data often used in ecological modelling, such as System Dynamics (Forrester,1961), might be inappropriate, since information available is inexact, uncertain, inaccurate, and incomplete. If our purpose is to generate explanations about the system's behaviour or to make rough predictions in educational contexts about the population's future, then we need models that allow symbolic reasoning in a flexible way, using conceptual schemes as humans do.

Qualitative Reasoning (QR) is an area of Artificial Intelligence which can be useful to deal with this kind of ecological problem, since it provides techniques to make inferences using symbolic data to represent physical quantities. Many different approaches have been proposed for qualitative modelling and simulation, particularly in physics (cf. Weld & de Kleer, 1990). QR has been used in ecology, for example in management of hydroecological systems (Guerrin, 1991), in environmental impact evaluation and in crisis management (Antunes *et al*, 1987), and in applications of ecological concepts to other sciences (Kamps & Péli, 1995).

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QR has its roots in the development of Intelligent Tutoring Systems (ITS) (cf. Brown *et al*, 1982; Wenger, 1987), and its techniques are now being used to develop learning environments (cf. Forbus, 1993b). Qualitative models can be used to generate articulated simulations of a particular system, and explanations about the system's behaviour. For students of ecology and biological sciences, experimentation with simulation models is particularly useful in order to obtain better understanding of how natural systems work. We intend to develop an ITS using qualitative simulations on aspects of plant population dynamics. Preliminary results are presented here in the following way: in the next Section an overview of the ecological problem to be modelled is given; in Section 3 different approaches explored so far are described, and in Section 4 their suitability to ecological modelling in an ITS is discussed.

2. Brazilian cerrado ecosystem

We are going to model relationships observed in a community of Brazilian cerrado, and the effects of fire on the population dynamics of some plant species. Cerrado is a kind of savanna that covers about 2 million square kilometres in the central region of Brazil, where the climate is tropical, with a well marked dry season between May and September, and a wet season, with 1100 - 1600 mm average rainfall per year. Cerrado presents great biological diversity and can occur in many natural physiognomies, depending mainly on edaphic conditions as soil fertility and the amount available of soil water during dry season (Eiten, 1982). Fire is an ancient factor present in these ecosystems, and many plant species have a great number of adaptations against its deleterious effects, such as the capacity to sprout from underground organs (xylopodia), even when aerial parts are completely burnt and destroyed. Fire also stimulates flowering in a number of species, and has positive effects on fruit dehiscence and seed dispersion, as well as on seed germination in some species (Coutinho, 1982; Frost & Robertson, 1987).

Cerrado is nowadays under great pressure due to farming and human occupation. It is important to study its characteristics and to develop awareness regarding its conservation. One strategy for quick action involves education. Tutoring systems can be useful in qualifying professionals of biological sciences. These systems can supplement field work and even replace it in some situations. An ITS can also be helpful in universities with a high number of students and small number of teachers – this is the case of Brazilian universities located in cerrado areas.

3. Qualitative approaches to ecological modelling

Qualitative models are in a relatively immature state and there is hardly an established methodology for using them. As a consequence, there is still need for much research on how to include qualitative simulations in a tutoring paradigm. An important aspect to think about is the possibility of producing explanations directly from the encoded knowledge, instead of using "canned texts". Systems that generate explanations are more flexible because it is not necessary to anticipate every possible question, the explanations are fitted to the current situation and to each student, and are always consistent, whether or not the knowledge base had been changed (Acker *et al*, 1991).

We have so far tried two different approaches for qualitative modelling: one based on Qualitative Process Theory (QPT) (Forbus, 1984) and another based on a formalism developed for the System to Interpret Measurements and Observations (SIMAO) (Guerrin 1991; 1992; Guerrin *et al*, 1994). The results obtained with them were compared with a model built using the quantitative System Dynamics modelling approach.

QPT models physical changes through *Processes*. They can be described by using statements about the objects and situations involved, the conditions needed to trigger the process, and the direct and indirect influences caused by the process. These direct and indirect influences have effects that propagate through the whole system being described and can be used to express causality. Therefore it is easy to generate explanations about a system's behaviour: changes in the system are explainable by the direct or indirect effect of physical processes (Forbus, 1993a). The process-centred approach is being used to develop educational tools, for example as described in (Forbus, 1993b).

SIMAO uses a formalism in which models are built after identification of the most relevant variables for a specific task. Relationships between these variables are represented through a causal graph and can be instantiated using primitive operators or combination tables in order to produce short term predictions about the system. In this approach an explanatory discourse is generated in three steps: assigning individual meaning to model input-values, calculating individual meaning for all the model variables by combining the qualitative values of input-variables, and expressing all the causal relationships between variables in the model (Guerrin, 1992). Explanation capabilities of SIMAO were used in diagnosis and management of complex systems, but not in educational contexts.

4. Discussion and future work

We used these two approaches to implement models about the same ecological problem and we got similar results in simulations with the same inputs. Compared with the quantitative model built using the System Dynamics framework, the results obtained with the qualitative models were also satisfactory. We could capture the most distinctive aspects of the population's behaviour, as for example in describing changes in number of plants due to different levels of dryness. Thus, to calculate the qualitative values of variables during simulations, any of them could be used in an ITS.

However, QPT is more general and offers a more robust theoretical background than the SIMAO formalism. State variables, flows and other elements from System Dynamics can explicitly be modelled in the QPT framework and therefore it is possible to produce more detailed ecological models than using the SIMAO formalism. Another shortcoming of the SIMAO formalism is that it does not deal explicitly with time, and thus it is not suited for dynamic simulations. Nevertheless, tools for handling temporal aspects of simulations are being developed (Guerrin *et al*, 1994) in order to overcome this limitation. In the process-centred approach dynamic simulations can be represented by using histories made up of episodes and events.

Explanations can be generated in both formalisms, but the possibility of representing direct and indirect influences in different ways in the QPT formalism is very important to explicit relationships between the variables in the model. To generate explanations in an ITS it can be particularly helpful.

As a conclusion we can say that, depending on the purposes of a model, both formalisms can be useful in modelling plant population dynamics. To develop an ITS QPT might be more recommended. We are now exploring other approaches for qualitative modelling of ecological problems, in order to produce an ITS for undergraduate students of ecology and biological sciences.

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Qualitative Models in Ecology and their Use in Intelligent Tutoring Systems

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Abstract

We are exploring different approaches to model qualitatively the vegetation dynamics of Brazilian cerrado, in order to assess their suitability to provide the domain-specific knowledge in tutoring systems. Two formalisms, the System of Interpretation of Measurements, Analysis and Observations (SIMAO) and the Qualitative Process Theory (QPT), are compared here in two aspects: capacity for making predictions about the behaviour of a plant population, and the generation of explanations from encoded knowledge. Both SIMAO and QPT-based models can produce similar predictions to those obtained with a numerical model of the same problem. SIMAO provides a useful qualitative algebra to make calculations with heterogeneous variables. However it is not possible to incorporate descriptions of the ecological components nor do dynamic simulations with the SIMAO-based model. On the other hand, QPT allows the encoding of qualitative knowledge and building more detailed models, but does not provide a qualitative algebra for combining empirical values of variables. Both SIMAO and QPT permit the generation of system-based explanations, whereas QPT might be more recommended to generate domain-based explanations. We also discuss the role of different organisational levels and scales of space and time in explaining the behaviour of ecological systems. A combined approach could be advantageous in building tutoring systems.

1. Motivation

Ecological modelling has been mostly based on mathematical models. Although useful when quantitative data are available and precision is required, this kind of approach is not adequate for representing qualitative and incomplete knowledge about ecosystems. It is also poorly-suited for teaching basic ecological principles: they are difficult to understand, and they lack explicit causal relations among variables.

Several approaches have been proposed for modelling and simulation with qualitative knowledge in Qualitative Reasoning (QR) (see Weld & de Kleer 1990). Some have been applied in building tools to predict the behaviour of ecological systems. They have been used, for example, in management of hydroecological systems (Guerrin 1991; Heller et al. 1995), modelling an irrigated crop system (Plant & Loomis 1991), modelling the photosynthesis process (Hunt & Cooke 1994), and applying ecological concepts to social sciences (Kamps & Péli 1995).

Our goal is to model the effects of fire on vegetation dynamics for educational purposes. Initially we are investigating the suitability of QR techniques in producing models that can represent domain specific knowledge in tutoring systems. The work reported here presents a case study in which two different QR approaches were used in modelling the same ecological problem: the System of Interpretation of Measurements, Analyses and Observations (SIMAO) (Guerrin 1991; 1992), and the Qualitative Process Theory (QPT) (Forbus 1984). The objective was to explore their potential to represent entities and relationships, make predictions and then generate explanations about the behaviour of a plant population. These approaches were chosen because SIMAO was developed in an ecological context, whereas QPT, among other traditional ontologies such as the component centred approach (de Kleer & Brown 1984) and the constraint centred approach (Kuipers 1986), is more adequate for representing declarative qualitative knowledge (Salles et al. 1996).

We will present our results in the following way: in Section 2 some characteristics of the ecosystem to be modelled, the Brazilian cerrado, are discussed. A problem is defined and represented as a System Dynamics numerical model, which will be compared to the qualitative models. The following two Sections contain details of qualitative models for the same problem, built according to SIMAO (Section 3) and QPT (Section 4). Results obtained with them are compared to those obtained in the numerical

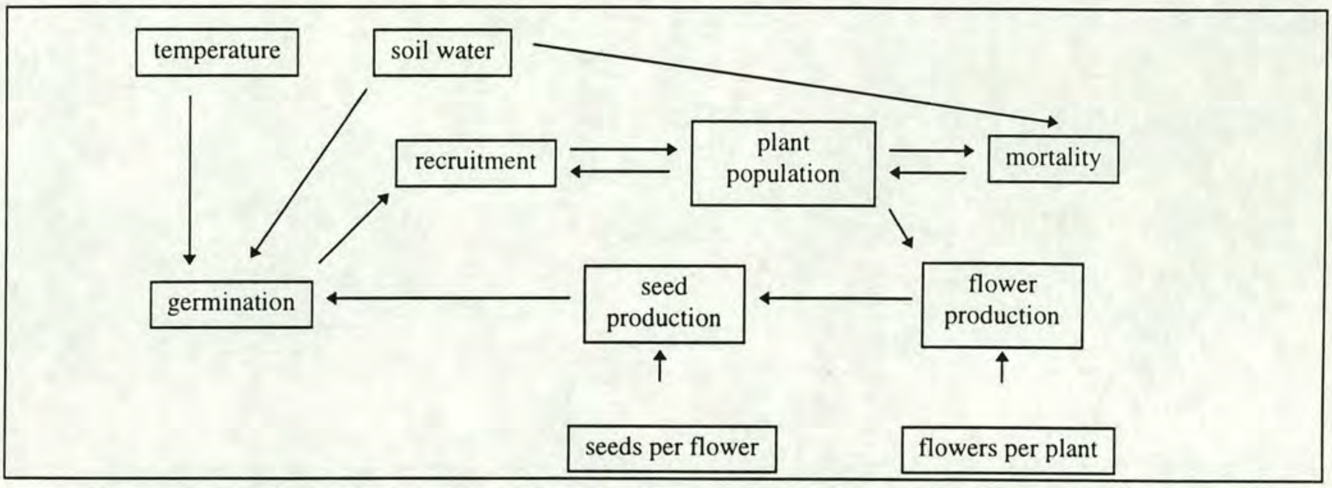

Figure 1. Influence diagram representing some factors that can affect the number of individuals in a plant population.

simulation in Section 5. The possibility of generating explanations from these qualitative models will be discussed in Section 6 and finally, in Section 7 we present our conclusions and possibilities of future work.

2. Describing a problem as a numerical model

Cerrado is a kind of savanna that covers about 2 million square kilometres in the central region of Brazil, where the climate is tropical, with a well marked dry season between May and September, and a wet season between October and April. This vegetation holds great biological diversity and can occur in many naturally well defined groups of plants, with a characteristic floristic composition (physiognomy), located at specific habitats (Eiten 1982). These physiognomies span from open fields to more or less closed forests. Fire frequency and intensity and some edaphic factors, such as the soil fertility and the amount of available soil water in the dry season, determine the type of vegetation in a given place. For example, if an area is protected against fire for a long time, and its soil is rich and deep, an open vegetation can change toward a forest.

Fire affects both the environment and the biological community in cerrado ecosystems in many different ways (Coutinho 1990; Frost & Robertson 1987). It reduces plant biomass and litter, alters energy, nutrient and water fluxes between soil, plants and atmosphere, changes availability and use of resources, and alters competition and other relationships between organisms. On the other hand, fire stimulates flowering and seed germination in some species, and can be used as a management tool.

Cerrado is nowadays under great pressure due to farming and human occupation. As we believe that any strategy for conservation involves education, our purpose is to build an Intelligent Tutoring System (ITS) to help teachers in communicating ecological knowledge about the cerrado. We found several elements that justify the development of an ITS for use in undergraduate courses in Brazilian universities. There are many students coupled with few instructors. Also, equipment for field work is expensive and most of the time it is not available. We believe that an ITS can supplement field work and even replace it in some situations, because experimentation with real systems is rarely possible.

The problem we choose to model for the present study can be illustrated by the following description: consider a scenario in which there is a large number of plants, the area has been burned recently, temperature is hot and soil is very dry. With these conditions, many biological processes can be inhibited, as for example, flowering, seed production and germination. Consequently, few flowers will be produced, there will be few seeds and many of them will fail to germinate. At the same time, some plants are going to die. Since changes in population size depend on the survival of young plants (recruitment) and mortality, intuitively we can say that in the described situation the population growth will be negative and the number of plants in the next time unit might be smaller. The set of relationships that we are trying to represent is described in the influence diagram showed in Fig.1.

System Dynamics (Forrester 1961) is probably the most used approach in ecological modelling. In this framework, a model consists of compartments and flows described through a set of differential equations. A model for the diagram in Fig.1 consists of one state variable (number of plants), three intermediate variables (number of flowers, number of seeds, number of germinated seeds), four parameters (average number of flower per plant, average number of seed per flower, soil condition and temperature), and two flows (recruitment of plants and mortality). To

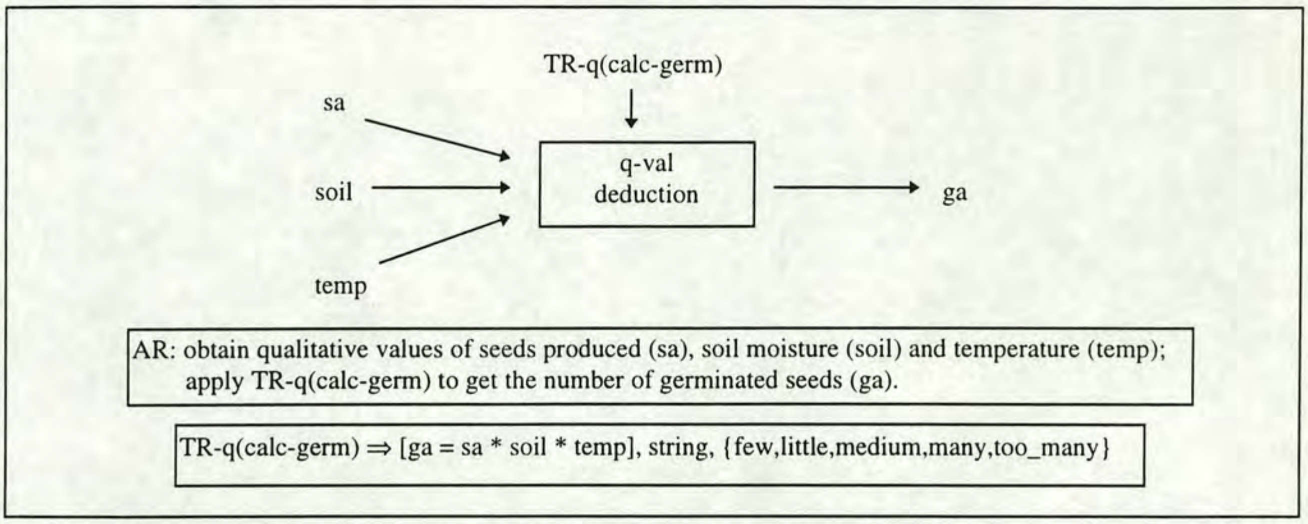

Figure 2. Knowledge Unit used to summarise inputs and procedures needed to calculate the number of germinated seeds.

implement this model we used FloMo, software developed by Robert Muetzelfeldt at the University of Edinburgh for educational purposes, in which the student can create his/her model and run numerical simulations without entering any differential equation. The results obtained with this model covering a wide range of situations will be compared with the outputs from qualitative models in Section 5. These qualitative models were implemented in Prolog and are described in (Salles 1994; 1995).

3. Modelling within the SIMAO framework

3. 1 The SIMAO formalism

The SIMAO formalism was developed by F. Guerrin (1991;1992) as a tool for the interpretation of measurements, analysis and observations commonly used in management of aquatic ecosystems. Here 'interpretation' means the ability to deduce, from a subset of input values, qualitative values of as many unknown variables as possible, and then to explain the reasoning process to give the user an overall comprehension of the phenomena (Guerrin 1992).

To encode expert knowledge, two main kinds of rules are used: *Transfer Rules* and *Action Rules*. Transfer Rules correspond to the representation of causal influences in the system, and three types are recognised: translation rules of measurements, translation rules of observations and calculation rules. Action Rules are used to control the application of the Transfer Rules. A qualitative algebra was empirically developed, based on three unary operators (increase, decrease, inverse) and three internal laws (addition, subtraction and multiplication), for combining influences between variables. These laws have some minimal properties (commutative, associative, distributive) required for calculus, as explained in (Guerrin 1992). All the statements needed to determine the value for a given variable constitute a *Knowledge Unit*. Knowledge units can be represented diagrammatically to show how input values (measurements, observations or other qualitative variables) are combined, how specific Transfer Rules and Action Rules are to be applied, and the expected output.

The SIMAO formalism was used originally in the domain of hydroecology, to make predictions about the parameters used in the management of fishponds. A subsequent application of SIMAO in controlling variables in a fermentation process is described in (Guerrin et al. 1994). However, it has never been used for educational purposes.

3.2 Developing a model and running simulations

To represent the number of plants, flowers, seeds, germinated seeds and dead plants, we used a Quantity Space (QS) with five symbols {*pp, p, m, f, ff*}, corresponding respectively to values {*very_few, few, medium, many, too_many*}. The same symbols were used to represent the qualitative values of soil moisture ({*very_dry, dry, medium, wet, very_wet*}) and temperature ({*very_cold, cold, mild, hot, very_hot*}). Two parameters were used to characterise the average number of flowers produced per plant and the average number of seeds produced per flower. For them, the QS was {*few, medium, high*}. Finally, a QS was defined to represent tendencies in population growth: {*decrease, stabilise, increase*}.

The model contains 10 Knowledge Units: one of them is presented in Fig. 2. Here, in order to calculate the number of germinated seeds, values for number of produced seeds, soil condition and temperature are required. An Action Rule (AR) explains the procedure and the specific Transfer Rule (TR) used is detailed. Inside the round brackets of TR there is information about how to combine the inputs to get the output, the nature of input values (number, string) and the QS for that variable.

The system first creates a list of the variables for which qualitative values can be calculated, and the user can either choose to calculate values for all or one of them. Depending on the selection, some particular inputs are needed, and the user is asked to introduce them. These values are asserted to the database and used to calculate the output variable(s). The system presents the results in an easily-understood language. The following dialogue (Fig. 3) shows a simulation in which it calculates the number of germinated seeds, using as input information about the number of plants, their ability to produce flowers and seeds, and conditions of soil and temperature.

Which variable from the menu do you want to calculate?
>> **Germinated seeds**

Please, enter the values of...
[number of plants, flowers per plant, seeds per flower, soil condition, temperature]:

>> **[few, medium, high, dry, cold]**

The value of germinated seeds is medium,
which is calculated from:
number of plants = few
average number of flowers per plant = medium
number of flowers = medium
average number of seeds per flower = high
number of seeds = too_many
soil_condition = dry
temperature = cold
yes

Figure 3. Simulation with the SIMAO-based model. Parts of the dialogue in which the user introduces information are presented here in bold preceded by the mark " >> ".

3.3 Some comments about the SIMAO-based model

Guerrin points out that SIMAO enables the processing of heterogeneous values: it is possible to combine variables that are not related in physical laws, but that are *de facto* associated in expert reasoning, such as colour of the water and production of oxygen (Guerrin 1991). This is an important issue in ecological modelling, because experts often combine several different variables that could not be fitted into mathematical equations. In our model, for instance, the general appearance of the soil condition (dry, wet) was related to germination and mortality in an easy and efficient way.

However, SIMAO does not provide tools for representing the system's temporal evolution, and therefore only allows static simulations. Although it is possible to explore many different and important aspects of the ecological knowledge using static simulations, this is a limitation in modelling changes observed on the vegetation dynamics, as in the present case. Nevertheless we should note that in actual ecosystems there are many different phenomena occurring at different time scales. Therefore, it is a hard task to deal with time dependent variation in both qualitative and quantitative ecological models.

Causality is expressed in SIMAO by causal graphs. It is therefore easy to follow the steps needed to calculate the value of a variable, and explanation can be given by tracing the calculations. A limitation of SIMAO in building educational tools is the impossibility of representing declarative qualitative information, for example describing the conditions for a seed to be considered mature, with its primitives. Considering the importance of this kind of knowledge in ecology, it is difficult to build more detailed models and to generate explanation for a student with this formalism, a point which will be discussed below.

4. Modelling within the QPT framework

4.1 Development of a model according to QPT

According to QPT, the world can be modelled as a set of *objects*, and things that cause changes in objects over time are intuitively characterised as *processes*. Processes affect objects in different ways, and many of these effects can be modelled by changing some properties of the objects (Forbus 1984). An object named *Plant*, that corresponds to the actual population of plants, is the main object in our model. *Plant* is classified as a composite object, because it can be decomposed into smaller parts, such as *Flower* and *Seed*. These also are considered as the collection of flowers and seeds produced by the population. The processes identified in the influence diagram presented in Fig. 1 are *Flowering*, *Seed_production*, *Germination*, *Recruitment*, *Mortality* and *Population-growth*. Each of these processes can be described according to the template used by (Forbus 1984).

As an example we will describe the process *Germination*. It occurs when the environmental conditions are favourable, and results in young plants (seedlings) being produced. The rate of production of seedlings is influenced by the number of seeds, temperature and soil condition. The number of plants is expected to increase while the number of seeds decreases, and these are the changes caused by process *Germination*. In QPT, this information is specified in five slots, as follows: a) *Individuals* contains lists of objects or entities upon which the process is applicable, such as *Plant* and *Seed*. b) *Preconditions* contains statements referring to external conditions unaffected by the process. For example, *Germination* requires the presence of a trigger, that is, something that starts germination, such as light, fire or a chemical factor. c) *Quantity Conditions* are statements about inequalities involving quantities of the objects that affect and are affected by the process. For instance, the number of mature seeds must be greater than zero for process *Germination* to occur. d) *Relations* include statements about relationships between variables that hold when the process is active, such as descriptions of new entities created by the process, and indirect influences between quantities induced by the process. In *Germination* a new quantity is created, *germination_rate*, and it cannot be negative. These influences are represented by *qualitative proportionalities* (α_Q). It is possible to distinguish positive and negative indirect influences (α_{Q+} and α_{Q-}). e) *Influences* contains statements that specify what can cause a quantity to change, through direct influence imposed by the process. For example, *germination_rate* is a direct and negative influence (I –) on the number of seeds, and a direct and positive influence (I +) on the number of plants. The set of slots used to describe process *Germination* is presented in Fig. 4.

Individuals:	*Plant* a composite object
	Seed part of a composite object (*Plant*)
Preconditions:	favourable (environmental conditions)
	presence of some trigger and water
Quantity Conditions:	[number_of (*Seed*)] > zero
Relations :	Let germination-rate be a quantity,
	¬ [germination_rate] < zero,
	[germination_rate] α_{Q+} [number_of (*Seed*)]
	[germination_rate] α_{Q+} [temperature]
	[germination_rate] α_{Q+} [soil_condition]
Influences:	I+([number_of (*Plant*)] , [germination_rate])
	I– ([number_of (*Seed*)] , [germination_rate])

Figure 4. Description of process *Germination* using the QPT primitives.

Qualitative proportionalities are used to describe how a certain quantity will change in its dependency on another quantity. Even without knowing the actual function relating them, it is possible to use these primitives to establish *correspondences* between values on the QS of both quantities. We used the qualitative calculus applied in the SIMAO-based model (cf. Section 3.2) to build these correspondences.

The collection of qualitative proportionalities is loop-free, that is, if $A\ \alpha_Q\ B$, then it cannot be the case that $B\ \alpha_Q\ A$. However, it is possible to model systems in which two variables are interdependent, such as feedback systems, by means of combining direct and indirect influences. This interaction, which is a general mechanism for controlling biological and ecological systems, can be represented as $A\ \alpha_Q\ B$ and I (B,A). For example, the rate of germination influences and is influenced by the number of seeds:

[germination_rate] α_{Q+} [number_of (*Seed*)]
I– ([number_of (*Seed*)] , [germination_rate])

Qualitative proportionalities and Influences are powerful primitives to be used in ecological modelling in building chains of causality. For example, what can cause an increase in the number of plants? There is a direct influence from germination rate. However, germination rate is influenced by the number of seeds, which is in turn influenced by *seed_production_rate*, a quantity created in process *Seed_production.* This last rate is influenced by the number of flowers and therefore depends on process *Flowering*. As we can see, this chain can be recursively expanded to include other environmental factors until the most important causal relationships acting on the number of plants are established:

I+ ([number_of (*Plant*)] , [germination_rate]
[germination-rate] α_{Q+} [number_of (*Seed*)]
I+ ([number_of (*Seed*)] , [seed_production_rate])
[seed_production_rate] α_{Q+} [number_of (*Flower*)]
I+ ([number_of (*Flower*)] , [flowering_rate])
(...)

In QPT, *Histories* are used to represent how things change through time. Although in our model there is a sequence of processes, each depending on the predecessor, which actually is a history, we did not fully explore this concept. We restricted ourselves to considering the simulation of population growth over just one time unit.

4.3 Some comments about the QPT-based model

We agree with Forbus (1993a) in that the notion of process seems natural in organising ecological knowledge, because processes play a central role in the way experts think about ecological systems. Also the possibility of expressing causality even in feedback loops with the basic elements of QPT makes it easy to generate explanations about the system's behaviour: any change must be explainable by the direct or indirect effect of a process. For example, we could combine factors as different as flowering, seed production and germination in a chain of causality, without knowing the actual functions that would relate them. This is particularly important in a tutoring system for ecological domains, in which having only partial knowledge about ecosystems is a quite common situation.

Applications of QPT so far rely on the understanding of physical laws and their mathematical expression involved on physical and engineering systems (e.g. Forbus 1984; 1993b). These laws are used to specify criteria to select values in composing each variable's Quantity Space, expressed as the *relevance principle* by Forbus (1984), and in combining values of different variables. However ecological models often include several variables, some with a wide range of possible and relevant values. Considering that there is no equivalent knowledge about ecological laws and mathematical formalisations to combine these heterogeneous variables, we adopted the qualitative algebra developed in SIMAO and later expanded as a Dualistic Algebra (Guerrin, 1995) to implement our QPT-based system. Predictably, this decision increased the similarity of the output from both qualitative models during simulation, as shown in the following Section.

5. Comparison between qualitative and quantitative models

In order to evaluate predictions made from the qualitative models, they were compared to the numerical output from the System Dynamics model. We assumed that there is a correspondence between the ranges of numerical values and the qualitative values included on the Quantity Spaces (cf. Section 3.2). For instance, if a state variable or an intermediate variable can assume values on the range 1 - 100, then we can divide it in five intervals, and relate them to qualitative values. Therefore the interval between 1 - 19 corresponds to *very_few*, 20 - 39 corresponds to *few*, and so on. We made some simulations using the intervals 1 - 1,000 and 1 - 10,000 and we obtained similar results.

We have also used in our models two different classes of parameters, one to represent the influences of temperature (*temp*) and soil condition (*soil*), and the other to represent intrinsic biological factors related to the production of flower and seed (*typef* and *types*). For *soil* and *temp*, an arbitrary numerical interval between 0.1 - 0.9 was associated with the qualitative values. For *typef* and *types*, each qualitative value was associated with a multiplication factor ranging from 1 - 3. As we did with the qualitative models, the System Dynamics model was used to run simulations over just one time unit. Therefore, given the initial number of plants and some other input values, the system calculated the number of plants on the next time unit.

Outputs from the three models were quite similar. Taking a sample of 45 simulations covering the whole range of qualitative values and relevant combinations of variables, in 33 cases the numerical value matched the qualitative value obtained from the qualitative models. In 8 simulations calculated numerical values were very close to qualitative ones (less than 10% above or below the limits for the corresponding qualitative interval). Finally, only 4 simulations produced different results in quantitative and qualitative models, that is, with differences greater than 10%. In all of them, the multiplication factor used to represent the average number of flowers per plant or seeds per flower was the main reason for the discrepancy. These results confirm our view that, in this context, and over a projection period of just one time unit, predictions derived from qualitative models are good approximations to those produced in quantitative simulations.

6. Generating explanations from qualitative models

According to Valley (1992), there are two types of explanation: system-based and domain-based explanations. The former describe what has happened during a consultation, for example, which rules have been fired and which facts have been deduced. To generate this kind of explanation, a trace of the consultation must be kept: this can be retrieved, translated and then presented to the user. Domain-based explanations contain information about the domain knowledge, and justify system-based explanations. Therefore, the system can explain not only the steps it takes during the reasoning process, but also the reasons for following these steps. This kind of explanation requires an explicit representation of the domain knowledge.

The explanatory capability of a SIMAO-based system is the ability to produce a transcript, at any time, of the execution trace of predictive reasoning inferences (Guerrin 1991). Accordingly, we could generate explanations where the calculated value of a variable is linked to the set of input values used during the calculation process. The dialogue showed in Fig. 3 illustrates this kind of system-based explanation. As the SIMAO formalism does not provide other primitives to encode related qualitative knowledge, it was not possible to generate domain-based explanations.

Similar system-based explanations can be produced from the QPT-based model. However, QPT allows a more complete representation of objects and processes, using frame-like slots to model individuals, conditions, relations and influences. Thus it was not difficult to generate a wider range of explanations within this framework. Some basic questions can be answered directly from the knowledge encoded with QPT primitives, such as: a) when does a process occur? b) what are the conditions for a process to happen? c) what are the changes caused by a process? d) what are direct and indirect influences causing on these changes? More explanations can be generated by using templates. The user is presented with a menu of questions the system can respond to, and then fills in the blanks specifying the explanation required. These explanations might draw on explicit, default and derived knowledge. Figure 5 shows some examples.

To understand and explain the behaviour of ecological systems we have to consider the different organisational levels at which biological systems can be studied. There is a hierarchy spanning from the sub-cellular level up to the biosphere, as follows: {subcell, cell, tissue, organ, individual, population, community, ecosystem, biosphere}.

>> **what_change_cause(germination)**
germination causes changes in
number_of(plant)

>> (why) **germination_rate indirectly_influenced_by number_of(flower)**
(The user enters a question using a template)

germination_rate indirectly_influenced_by
number_of(flower)
because
the property is derived for germination_rate
yes

Figure 5. Explanations in the QPT-based model.

Ecological knowledge covers mainly the levels ranging from the individual to biosphere. These organisational levels also reflect spatial and temporal scales. For an example compare the dimensions of individuals and ecosystems, which may cover hundreds of square kilometres over centuries.

This hierarchy associated with organisational levels substitutes the "first principles" in the reasoning of ecological modellers (Plant & Loomis 1991). From a pragmatic point of view, given the behaviour of an entity at any level, we should look for explanations in levels below, and the consequences might be found on the levels above that one. We expect that this general principle will be useful to solve ambiguities. This problem was not addressed in the present work because all possible ambiguities in the behaviour of the described ecological system were solved by hand using domain specific knowledge.

There is no scale that can account for all aspects involved in an ecological system. It is therefore necessary to select which are the most relevant information, and leave the noise outside the model when scaling up and down (Levin, 1992). The time scale can be used in selecting relevant variables to answer a particular question, but time alone is not enough in more complex situations (Rickel & Potter 1995). We believe that, for educational purposes, explanations would require not only time and space scaling but also explicit references to different organisational levels. An example of explanation from the QPT-based model, in which a variable at the population level (germination_rate) is linked to processes at the individual (embryo development) and sub individual levels (storage of nutrients and enzymatic activity), is presented in Fig. 6. A forward-reasoning approach could transform this explanation into a prediction about the consequences of the particular values for the state and the number of seeds.

:- **ask_explanation(germination_rate_is_high)**
germination_rate_is_high because
activity_of_enzimes_is_maxima and
number_of_seed_is_high.
activity_of_enzimes_is_maxima because
temperature_is_hot and soil_is_wet and
seed_can_germinate
seed_can_germinate because
there_is_trigger and there_is_water
and seed_is_mature
seed_is_mature because
embryo_is_developed and
enzimes_are_ready and nutrients_are_stored
yes

Fig. 6 Explanation in the QPT-based model.

7. Conclusions and ongoing work

In this paper we described a case study where we explored the possibility of representing knowledge, making predictions and generating explanations about the behaviour of an ecological system using two QR formalisms, SIMAO and QPT. Three models representing a set of relationships among the most important variables in a plant population's life cycle were implemented. One of them was a numerical model built within the System Dynamics framework, and the two other were qualitative models based on SIMAO and QPT.

SIMAO allows combining the heterogeneous variables involved in ecological modelling through an efficient qualitative algebra. This formalism does not deal explicitly with time, and therefore it is not adequate to be used in teaching vegetation dynamics. On the other hand, QPT is more general as a formalism and allows descriptions containing qualitative knowledge about entities, relationships and conditions. Thus it is possible to build more detailed ecological models using this approach. However, QPT does not provide a qualitative algebra for combining empirical values of variables. In implementing our QPT-based model we used the qualitative algebra developed in SIMAO. Similar predictions can be made by running simulations with both quantitative and qualitative models. Within the limits of the present work, we could capture the most distinctive aspects in the behaviour of a plant population under different environmental conditions with either the quantitative or the qualitative approach.

We can generate system-based explanations in which results from the simulations are justified by input values and intermediate calculations using both QR formalisms. However this kind of explanation is not enough to support the explanatory capabilities needed in a tutoring system. Domain-based explanations can be produced with the QPT-based model, given the possibility of encoding qualitative ecological knowledge and representing with different primitives direct and indirect influences acting on variables.

We discussed also some problems we found in organising large amount of knowledge without having clearly stated ecological laws. Explanations and predictions about ecological systems behaviour often refer to either higher or lower organisational levels and to different scales of space and time. It is necessary to adopt a great variety of perspectives and to select only relevant information when answering questions in tutoring systems. We believe that time, space, and the organisational levels will also be required in evaluating the importance of variables in particular contexts and in solving ambiguities.

As a conclusion we can say that, depending on the purposes of the model, both formalisms can be useful in modelling vegetation dynamics. QPT might be more recommended for formalising knowledge and support automatic generation of explanations in an educational context. On the other hand, SIMAO can provide a qualitative algebra combining heterogeneous variables during simulations. A combined approach can be profitable in developing a tutoring system.

We are currently improving the explanatory capabilities of the prototype QPT-based system, and implementing models with more detailed knowledge about the effects of fire on the cerrado vegetation. Our future work has to address some problems that are challenges for the whole QR community: how to build systems that do not use numerical simulations but instead rely almost entirely on qualitative knowledge? How to handle large models efficiently? How to overcome the scaling problem in capturing the same ecological phenomena at different levels of granularity? And last, but not least, how these models will behave in real classrooms?

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Qualitative Ecological Models for Tutoring Systems: a Comparative Study

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Abstract: In this paper we compare three qualitative reasoning ontologies, the *component*, the *constraint* and the *process*-based approaches, according to their suitability for building ecological models. Our purpose is to use these models as domain knowledge in a tutoring system. Comparison was done by representing an ecological problem about plant population. Population growth can be described by qualitative and quantitative knowledge about seed production, recruitment and mortality. We explored some aspects of the three approaches in respect to their ability to represent the model's structure, variables, constraints, quantity spaces, state transitions, and causal relations. Difficulties in explaining behaviour from results obtained in simulations are discussed within each framework. Different domains of ecological knowledge might be better represented using different ontologies. Domains where quantitative knowledge is more relevant can be represented using the three formalisms. When declarative, qualitative knowledge is predominant in a domain, the process-based ontology is more promising. We present an evaluation of the three ontologies in modelling different parts of the curriculum usually found in textbooks, and discuss some problems related with explanation and prediction about ecological systems.

1. Introduction

Computer models so far created by ecologists to represent ecological systems are based on mathematical equations. Thus behaviour of these systems can be described by exact values of their variables at each time instant. Although providing a precise description and means for evaluation, these quantitative models are difficult to formulate and calibrate. They are also inadequate for representing much of the incomplete, imprecise, and qualitative knowledge needed to explain ecological systems' behaviour.

In a certain way, we are in the same situation that stimulated researches in qualitative physics. As pointed out by de Kleer & Brown (1984), outstanding problems in physics, education, psychology and artificial intelligence motivate the development of a qualitative physics, to predict and explain the behaviour of physical systems in qualitative terms. Ecologists also are in need of modelling approaches that are simpler than those so far used in ecological modelling, and yet retain all the important distinctions, without invoking mathematical equations. As we are particularly interested in ecology teaching, we are looking for qualitative models that are easy to understand to produce causal accounts of the ecological mechanisms. These models will provide the domain knowledge module in an intelligent tutoring system (ITS).

Some of the most important work in early stages of qualitative physics were related to educational projects. SOPHIE, for example, was designed to support learning about electronic troubleshooting (Brown, Burton & de Kleer, 1982). SOPHIE was built on the top of quantitative simulators, with a set of mathematical formulae to express the system's behaviour, and facilities to interpret (qualitatively) the results. Koning & Bredeweg (1995) noted two important aspects that are missing in such quantitative models. The first is a representation of causality: we might consider that 'force causes acceleration', but this notion of causality is not expressed in the formula $F = m.a$. Secondly, a representation of the physical structure of the system being modelled is needed. A teaching program should be able to explain how a system is functioning and why certain behaviour emerges. Both causality and physical structure appear to be important for achieving these goals. Research in these topics has grown into an area now known as qualitative reasoning (QR) (Koning & Bredeweg, 1995).

Qualitative Reasoning has produced a wide range of different representations and techniques, and a general view of the field can be found in (Weld & de Kleer, 1990). QR techniques have been applied to ecological problems.

for example, by Guerrin (1991; 1992), Hunt & Cooke (1994), and Heller et al.(1995), but not in teaching. We believe that QR can provide the tools we need to develop the domain knowledge module in an ITS for ecology. We will explore here three of the most important QR ontologies: the component-based (de Kleer & Brown, 1984), the constraint-based (Kuipers, 1986) and the process-based (Forbus, 1984) approaches, examining their suitability for modelling an ecological problem, and the possibilities for explanation generation. In Section 2 we will identify a problem to be modelled and discuss some characteristics of a System Dynamics model for this problem. In Section 3 an overview of the three chosen QR ontologies is presented and illustrated using our model. Some comments about our needs and what QR offers are discussed in Section 4, and in Section 5 we present our conclusions.

2. An ecological problem and its numerical model

Suppose we want to model the behaviour of a plant population under different conditions, to communicate the knowledge involved to undergraduate students. Plants germinate from seeds, grow up, produce flowers which might produce seeds, and die (although death can occur at any stage of their life). A plant population can be increasing, decreasing or stabilised over a certain period of time. In order to simulate these behaviours, our model's structure should include, perhaps, the plant population, the available stock of seeds, and appropriate flows. The inflow, recruitment, represents the portion of seeds that germinate and produce new plants that are incorporated to the population. The outflow, mortality, represents the death of plants that have actually been introduced to the population by means of the recruitment. This is a problem that involves much quantitative knowledge.To explain behaviour of this population, qualitative information might be necessary, such as concepts about flowering and pollination, and knowledge about some environmental factors (behaviour of seed-eater animals, solar radiation, etc. See Table 3).

A System Dynamics (Forrester, 1961) model of the problem described above might contain one state variable (number of plants), an outflow (mortality), and an inflow (recruitment) influenced by an intermediate variable (number of seeds) which in turn is influenced by the population size. The structure of the system could be represented by a differential equation. However formulation and calibration of this equation is not easy. Considering that the biological meaning of some variables may become obscure, and the already mentioned lack of explicit causality, it is difficult to interpret and to explain the results obtained with the model.

3. Qualitative models

The task of QR systems is to assemble a set of model fragments (elements of domain knowledge stored in a library), impose a closed-world assumption and transform these fragments into a model capable of supporting simulation (Kuipers, 1994). Simulation in some approaches produce a graph (envisionment) with all possible behaviours under a given set of conditions. In other cases the graph contains all possible behaviours following an initial state (behaviour tree). Ontologies studied in this paper differ in many aspects, as discussed below. There are some interesting papers comparing these three ontologies with respect to physical systems, such as Bredeweg (1992), Bonissone & Valavanis (1985), and Fouché et al. (1989).

3.1 Modelling according to the component-based approach

Three kinds of constituents are considered in the component-based approach: materials, components and conduits. System's behaviour is accomplished by operating on and transporting materials. Components can change the form and the characteristics of materials, and conduits transport material from one component to another, but do not change any aspect of the material being transported.

The central modelling tool is the *confluence*, a qualitative differential equation. For example, qualitative behaviour of a plant population can be expressed by the confluence $\delta N = R - M$, where δN is the variation in the number of plants, R is recruitment, and M is mortality. A confluence relates multiple tendencies: recruitment influences positively the population growth, while mortality influences it negatively. However, a single confluence rarely can characterise the behaviour of a component over its whole operating range. The range must be divided into different regions, each of which is described by a different set of confluences. The assignment of values to every variable in the confluences in a particular region defines a *qualitative state* (de Kleer & Brown, 1984). For example, qualitative states for plant populations can be 'increasing', 'stable', 'decreasing'.

Qualitative variables can only take one of a small number of values, determined by its *quantity space*. A qualitative algebra is required in order to combine these qualitative values. In the component-based approach, a simple quantity space to represent whether a quantity is increasing, decreasing or unchanging ({+, 0, -}), is enough for most of the applications. This is not the case in ecological modelling. Very often it is necessary to represent and combine a wide range of qualitative values for heterogeneous variables (Guerrin,1991;1992).

Each component is represented by a component model that consists of the confluences which describe the component's behaviour and the set of possible qualitative states, including *specifications* (statements about the conditions for the state to be active). Table 1 represents the component model for the plant population:

Table 1. The component model for plant population.

component	qualitative states	specifications	confluences
plant population	increasing	R > M	$\delta N = +$
	decreasing	R < M	$\delta N = -$
	stabilised	R = M	$\delta N = 0$

As the system evolves, qualitative values of the variables change, causing transitions between states. State transitions are governed by some rules, and each qualitative behaviour of the device being modelled is a path through the state transition diagram. Diagrams containing all the possible states resultant from solving the confluences, and a causal account for the behaviour constitute the total *envisionment*.

Envisionment is done in two stages. First, all the possible states for each individual component are determined and combined with all the possible states of the other components in the model. This is called the *intrastate analysis*. For example, intrastate analysis should reveal how the value $\delta N = +$ (state 'increasing' of the population) would propagate in the system and change values in confluences of the other components, such as the seed bank, recruitment and mortality. The second stage is the *interstate analysis*, when all the legitimate transitions between states are determined. In our example, if the population's state is 'increasing', then the following state can be either 'increasing' or 'stable' but not 'decreasing', because qualitative values cannot be skipped (the so called *continuity rule*).

Qualitative reasoning is concerned with both prediction and explanation. de Kleer & Brown (1984) define explanation as the execution trace of whatever algorithm is used to make a prediction. Explanation and prediction are intrinsically linked: every syntactically valid explanation must describe a possible prediction. Thus, an explanation consists of a sequence of statements where each is justified by previous statements in the sequence. These authors used the logical proof to explain system's behaviour. However, the explanation-proof is inadequate as a theory of explanation, because of some undesirable characteristics. Steps in the explanation do not follow any notion of causal order, they move on from input to output in interstate behaviour. Thus explanation-proof explains *why* the device must behave, not *how* it behaves.

To explain how a behaviour is achieved, it is necessary to explain what happens when the system is stable (intrastate behaviour). To satisfy this ontological principle, de Kleer & Brown (1984) introduced the concept of *mythical causality*. This concept was later challenged by Iwasaki & Simon (1986), to whom mythical causality was similar to already known methods to derive causality from a system of equations, such as *causal ordering* and *comparative statics*. A deeper analysis of causality and its role in generating explanations in tutoring systems is quite important, but it is beyond the scope of the present paper.

The component-based approach and these researches in causal reasoning were developed in electronics, a domain where real systems (devices) are closer to idealisations (models) than ecology. Devices have well-defined topologies, with components that perform their behaviour according to well-established physical laws, and they are built to achieve specific behaviours (teleological systems). Ecological systems hardly share these characteristics. However, we can see a role for the component-based ontology in modelling controlled micro-ecosystems, such as the crop-irrigation system described in Plant & Loomis (1991).

3.2 Modelling according to the constraint-based approach

In the constraint-based approach, there is neither explicit representation of entities from the real world, nor libraries of models fragments. Models must be created by hand. The starting point is the *qualitative differential equation* (QDE), which is an abstraction of the ordinary differential equation. The constraint-based approach is not a complete ontology as are the other two studied in this paper, it is rather a qualitative mathematics, formalised to support the prediction of behaviour from qualitative constraint equations. Constraint-based models can be generated either by re-writing ordinary differential equations, or by creating QDE from descriptions of the system's causal structure (for an example, see Kuipers & Kassirer, 1983).

Quantity spaces contain values that represent the boundaries for describing qualitative distinct behaviours, called *landmark values*. The qualitative state of a variable can be a landmark value or the interval between landmark values. It is possible to create new landmark values during simulation, that might represent unexpected behaviours. The qualitative state of a variable is specified by a pair $< qval, qdir >$, respectively the qualitative value of the variable (qval. a landmark value or an interval between two landmark values) and the direction of change (qdir. the sign of the first derivative with respect to time). Time is represented as a sequence of points. as in the component-centred approach. When something interesting happens to any variable. a new time point is created. A state description with values for all variables is given at every time point.

Qualitative simulation consists of simulating the system forward from some initial state. Rules are used to determine the possible state transitions. It follows a generate-and-test algorithm: first generate all the possible successors from the initial state and then filter the solutions according to some constraints. When multiple possibilities occur. new branches are derived to accommodate all legal transitions. The result is a graph (the behaviour tree) containing all the states that can follow the specified initial state. Any path in this graph represents a possible behaviour. However. some of these behaviours are redundant (repetition of the same states) or spurious (physically impossible). and filters have to be used to avoid them.

There are seven types of constraints: arithmetic (addition. minus and multiplication). derivative. monotonic (increase. decrease). and constant. Some are straight forward relationships. such as add(x. y. z) to represent $x + y = z$. and deriv(x.y) to represent $dx/dt = y$. The functional constraints monotonic increase (M^+) and monotonic decrease (M^-) express incomplete. qualitative knowledge about a functional relationship. To model the plant population problem. variation in plant number must be related to recruitment and mortality. The result is the following set of qualitative equations: deriv(N.n). It follows that $n = R - M$. This can be re-written as $R = n + M$ and then represented as add(n.M.R).

There are ecological examples of qualitative simulation. such as a predator-prey system (Kuipers. 1994). However. the constraint-based formalism alone is as inadequate for building tutoring systems as numerical models. There is no explicit representation of the causal relationships. The only causal relationship available is the output sequence of values obtained after constraint satisfaction. We are again trying to derive causal accounts from QDE in order to produce causal explanations. perhaps by means of techniques such as mythical causality. comparative statics or causal ordering. The constraint-based approach can be combined with other approaches to overcome these problems. For example. Rickel & Porter (1995) used a model builder (QPC) that combines the constraint-based and the process-based approaches to make predictions and answer questions about biological and ecological systems.

3.3 Modelling according to the process-based approach

In the process-based approach. a structural description of the model is given by a set of *individual views* and *processes*. The former describes objects and situations. the later are the only mechanisms that promote changes in behaviour. Characteristics of objects are represented by quantities. and the qualitative state of a quantity is a pair *<amount.derivative>* . Changes in their values mean changes on qualitative states. and therefore change in behaviour. Each quantity is associated with a partially ordered set of qualitative values. its quantity space. Some elements in this set can be *limit points* (if they correspond to discontinuous changes in the system). and others can determine when a process may start or stop. The task of checking if variables have reached limit points is called *limit analysis*.

The process-based approach uses the concept of *histories* to describe the behaviour of an object over time. Since objects are often involved in more than one process. they have a process history. Also there is a variable history because each variable has its own distinguished time points. A complete object history is made up by these two kinds of histories.

Table 2. The process Seed_production.

Individuals:	*Plant* a composite object.
	Flower part of a composite object (*Plant*):
Preconditions:	favourable environmental conditions:
Quantity Conditions:	[number_of (*Plant*)] > zero.
	[number_of (*Flower*)] > zero:
Relations:	There is *Seed* part of a composite object (*Plant*).
	Has_Quantity (*Seed*. number_of).
	[number_of (*Seed*)] ≥ zero:
	Correspondence([number_of(*Seed*)]. [number_of(*Flower*)]):
	Let seed_production_rate be a quantity.
	[seed_production_rate] ≥ zero.
	[seed_production_rate] α_{Q-} [number_of(*Flower*)];
Influences:	I+ ([number_of (*Seed*)] , [seed_production_rate])

Behaviour of the plant population emerges from a combination of the following processes: Seed_production, Recruitment, Mortality and Population_growth. A process is described by five parts: individuals, preconditions, quantity conditions, relations and influences. An individual view is in turn described by four parts: the same first four parts of the process description. An example (process Seed_production) is given in Table 2.

The slot *Individuals* contains lists of objects or entities upon which the process is applicable, such as plants and seeds. *Preconditions* contains statements referring to external conditions. For example, seed production requires some environmental factors that could be explicitly represented such as water, light, and nutrients. *Quantity Conditions* are statements about inequalities involving quantities of the objects, which can be used to determine whether or not a process is active. *Relations* are statements about relationships between variables. Descriptions of new entities created by the process (such as seed) are also presented here (in contrast to the component-based approach).

Two primitives are very important in describing the relationships between variables: *correspondences* and *qualitative proportionalities*. Correspondences can be used in mapping values from the quantity space of one variable (for example, number of seed) to values in the quantity space of another variable (number of flower). Qualitative proportionalities (α_Q) express unknown monotonic functions between two variables. If, for instance, the function is strictly increasing, then a positive qualitative proportionality (α_{Q-}) is used. In our model the growth_rate is related to recruitment and to mortality in process Population_growth as follows:

$$[\text{growth\_rate}] \; \alpha_{Q+} \; [\text{recruitment}]$$
$$[\text{growth\_rate}] \; \alpha_{Q-} \; [\text{mortality}]$$

These qualitative proportionalities are similar to the functions M+ and M− used in the constraint-based approach. However, they can be used to build equations. We could re-write the proportionalities above as

$$[\text{growth\_rate}] = [\text{recruitment}] - [\text{mortality}]$$

In the process-based formalism dynamic aspects are expressed by the notion of direct influence. Direct influences can only appear in Processes and are presented in the slot *Influences*. In Table 2, for example, changes in the number of seeds are directly influenced by seed_production_rate, and this influence is positive. A single direct or indirect influence statement does not determine, by itself, how the quantity it constrains will change. Its effect must be combined with all the other influences acting on that quantity to ascertain their net effect. The operation of combining these influences is called *influence resolution*. State transitions depend on influence resolution and limit analysis. Simulation in this ontology produces total envisionment. In this graph nodes represent sets of active views and processes at each qualitative state.

Causality is expressed by means of direct and indirect influences. It is assumed that only processes can cause changes, either directly or indirectly. Influences and qualitative proportionalities are unidirectional: both I(A,B) and A α_Q B express ' B cause changes in A', directly or indirectly. There is a strong sense of direction in causal relationships within this ontology, that can be made explicit using its primitives. For instance, how could we explain an increase in the number of plants in a population? We know that the immediate cause is an increment in growth rate, which is the direct influence on number of plants. However there are other influencing factors that could affect growth rate, such as recruitment, number of seeds and flowers, and mortality. Recruitment is in turn influenced by the number of seeds available. Recruitment and number of seeds are indirect influences on the number of plants, because they influence first the other quantities. This chain of causality is expressed as follows:

$$I+ ([\text{number\_of (plant)}] , [\text{growth\_rate}])$$
$$[\text{growth\_rate}] \; \alpha_{Q+} \; [\text{recruitment}]$$
$$[\text{recruitment}] \; \alpha_{Q+} \; [\text{number\_of(seed)}]$$

The possibility of encoding declarative knowledge, and the explicit representation of direct and indirect influences are characteristics that recommend the process-based ontology to be used in modelling ecological systems for educational purposes. We have implemented a prototype system in Prolog using this formalism, and explored the possibility of automatic generation of explanations from the qualitative model (Salles et al. 1996).

4. Qualitative models and ecological education

To build an ITS we need models that represent explicitly the ecological knowledge, and that express causality for generating explanations. Ecology includes both qualitative and quantitative knowledge. 'Qualitative knowledge' refers to static descriptions of objects and situations, and also to qualitative information about dynamic aspects of the system. 'Quantitative knowledge' refers to attributes numerically represented, and quantitative information about the system's dynamics.

Although there will always be a mixture of the two in any sub-domain of ecology, Table 3 presents the curriculum normally found in textbooks for undergraduate students, classified according to the predominant kind of knowledge in the domain (qualitative or quantitative).

Table 3. Classification of ecological knowledge.

1. Biomes. Ecosystems. Food chains and webs. Characterisation of different actors: autotrophic and heterotrophic nutrition: herbivores. carnivores. etc. Qualitative knowledge.
2. Flux of energy: The flow of energy within the ecosystem. and along food chains. Importance of cellular processes such as photosynthesis. respiration. The basic laws of thermodynamics. Quantitative knowledge.
3. Biogeochemical cycles: Descriptions of processes and functional aspects of nutrient cycling. The movement of nutrients between soil. water. atmosphere and organisms. Qualitative and quantitative knowledge.
4. Physical factors. Influences of climate. temperature. etc. on the organisms. Mainly qualitative knowledge. some quantitative knowledge.
5. Population dynamics: births. deaths. and population growth. Mainly quantitative and some qualitative knowledge.
6. Communities. Succession. Intra and interspecific relationships. The niche concept. Biological diversity. Mostly qualitative knowledge.
7. Resource management. Conservation. Human ecology. Mainly qualitative knowledge. some quantitative knowledge.

Each of the three approaches compared here have characteristics that make them more adequate to support some aspects of teaching ecology. The component and the constrain-based approaches depend on qualitative versions of differential equations. and are more adequate to represent quantitative ecological knowledge. In situations where numerical models can be used. such as those found in items 2. 3. and 5 in Table 3. these approaches can be useful. However. qualitative ecological knowledge cannot be modelled with their primitives. They are not adequate to domains such as 1. 4. 6. and 7. On the other hand. the process-based formalism gives the widest coverage for the domains expressed in Table 3. Its primitives provides means to deal with both quantitative and qualitative knowledge. It is the best of the three approach to represent common-sense knowledge, that is needed in items 1. 4. 6. and 7. but it is not as well formalised as the other two approaches.

To express causality in ecological systems. often we refer to the hierarchy of organisational levels at which biological systems can be studied (such as cell. organ. individual. population. community. ecosystem). As a general principle. given a fact at any level. we should look for explanations in levels below that one. For example. recruitment (a population's attribute) can be explained by facts occurring on individuals (such as seed production. survival). On the other hand. consequences from a given fact might be found on the levels above (consequences of recruitment can affect the community and the ecosystem). Given that ecological laws are less known than physical laws. this hierarchy associated with organisational levels substitutes the "first principles" in the reasoning of ecological modellers (Plant & Loomis. 1991). In the context of QR-based systems. where ambiguity is common. this is a sensitive point.

As a consequence. the same phenomena must be captured at different levels of granularity. To answer questions in an ITS it is necessary to adopt a great variety of perspectives and to select only relevant sub-sets of possible behaviours. In fact. these are crucial problems because QR-based systems are inefficient to handle large models.

Our ongoing work address some of the aspects discussed here: we are modelling the effects of fire on the Brazilian cerrado vegetation with the apparatus provided by the Qualitative Process Theory (Forbus. 1984). and the qualitative algebra developed by Guerrin (1991: 1992).

5. Conclusions

In this paper we compared three QR formalisms (component. constraint and process-based approaches) according to the possibility of modelling an ecological system and generating explanations about its behaviour.

The component-based approach can be used to model controlled ecological systems. such as irrigated crop systems. with well defined topology and predictable behaviour. It is adequate to represent ecological knowledge in domains where quantitative knowledge plays a central role. such as flux of energy and population dynamics. The logical formalisation of this ontology and related studies about causality are a good starting point for the development of a general theory of explanations for ecological modelling and tutoring systems.

The constraint-based approach has no means of representing everyday knowledge about the environment. There is no explicit representation of causal relations. It is a well developed mathematical formalism to deal with qualitative constraint equations. It is adequate for situations that can be represented adequately by differential equations, such as population dynamics. It can be useful in ecological modelling and tutoring systems when it is combined with other approaches.

The process-based approach is more adequate for modelling a broader range of ecological knowledge for educational purposes. It provides the means necessary for representing qualitative knowledge, which is important to explain behaviour of ecological systems. This view is supported also by the way causality is represented in process-based models. Our intuitive notion of causation is related with propagation of changes. Considering that all changes are caused by processes, and that influences and qualitative proportionalities are directed representations, there is a strong sense of direction given the way causality is expressed in process-based models.

There are many open questions, such as the use of different organisational levels of biological systems to support explanation and prediction about ecological systems, and the need for representing the same phenomena at different levels of granularity. We are confident that QR techniques are useful to address these problems.

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Building Qualitative Models in Ecology

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Abstract

Building qualitative models is a difficult task. The construction of re-usable models, as well as the formalisation of the modelling process itself, are goals both to researchers in qualitative reasoning and ecology. This paper presents a library of model fragments for reasoning about the behaviour of ecological communities. We have developed a kernel of partial models that represents general knowledge about populations, which can be (re-)used in different situations. In addition, this paper discusses guidelines for the construction of qualitative models, based on our experience in representing the ecology of fire in the Brazilian cerrado vegetation. Our aim is to explicate the decisions we took during the construction of our models and to reformulate them as (more) general guidelines for the construction of qualitative models. Understanding the modelling process is a first step towards realising modelling support.

1 Introduction

The use of qualitative models in teaching situations is problematic for a number of reasons. There are hardly any easy to use tools available to aid the model construction process. It usually requires programming skills to build a simulation. As a result, the set of 'available' qualitative models remains small and is largely restricted to rather technical domains (e.g. physics). This is a second important bottleneck for using qualitative simulations for teaching: there is no large library of predefined domain models (or full qualitative simulations) that can be (re-)used by teachers in different situations. This is particularly true for non-physics domains.

In this paper we present a library of model fragments (cf. [Falkenhainer & Forbus, 1991]) for reasoning about the behaviour of ecological communities. In addition, we present guidelines for the construction of qualitative models, based on our experience in representing the ecology of fire in the Brazilian cerrado vegetation. Both the guidelines and the library of model fragments are part of a larger research effort in trying to use qualitative techniques as a basis for Interactive Learning Environments (ILE) (see also [Bredeweg & Winkels, 1996]). Our application domain is ecology. There is a growing concern about the world-wide destruction of natural resources. There is a need for educational tools that will contribute to the ecological awareness by learners. We believe that qualitative models can be the basis for some of these tools [Salles *et al.*, 1997].

After many years of developing representations and formalisms to reason qualitatively about physical systems, the qualitative reasoning community starts to recognise the importance of the modelling process itself [Schut & Bredeweg, 1996]. A related observation can be made within the community of ecological modellers. They are also trying to formalise the modelling process in order to recognise the principles that can be used by the modellers to explicate their intentions while modelling [Muetzelfeldt, 1991]. One important goal is to have a library of partial models, and a model construction environment, that can be used by ecologists to build their own models [Robertson *et al.*, 1991].

A few models of ecological systems have been created using qualitative techniques. For example, [Guerrin, 1991] and [Heller *et al.*, 1995] describe hydroecological systems, and [Hunt & Coke, 1994] modelled the photosynthesis process. [Kamps & Gábor, 1995] describe the implementation of a model about the logistic equation applied to the organisational theory. However, none discusses the modelling process in itself.

The contents of this paper is as follows. Section 2 introduces the ecological domain that we are dealing with. This section also briefly discusses the need for education within this domain and the importance of qualitative models for that purpose. Section 3 contains a brief description of GARP [Bredeweg, 1992], the qualitative simulation environment that we use for implementing our models. The guidelines for the modelling process are described in Section 4. Section 5 presents the qualitative simulation model that we have constructed of the cerrado vegetation. Finally, Section 6 presents our results and discusses ideas for further research.

2 Ecology in Brazilian Cerrado

The central region of Brazil is covered by a vegetation called cerrado. This huge area of almost 2 million square kilometres is characterised by a tropical climate, with two well marked seasons (wet and dry), and by soils that have low fertility. Within the cerrado vegetation it is possible to identify several types of cerrado physiognomies, spanning from open grasslands to more or less closed forests (see Figure 1). These

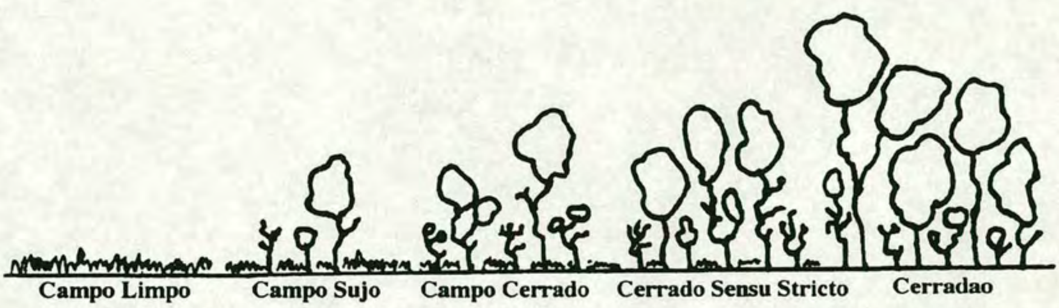

Figure 1: Typical classification of the cerrado vegetation

physiognomies have well defined floristic composition and are mainly determined by fire, soil fertility and the amount of water available in the soil during the dry season. Researchers have investigated the effects of fire on the cerrado (e.g. [Coutinho, 1990; Miranda *et al.*, 1996]). It has been shown that fire can affect both physical and biological factors: fire causes changes on

- the energy flux,
- water and nutrient cycles,

- the species composition of communities,
- the biomass in many plants, and
- stimulates flowering and germination of seeds in many species.

Fire can therefore be used as a management tool, for example to stabilise the vegetation in certain areas, and to reduce the risk of big fire events (cf. [Pivello, 1992]).

Cerrado is nowadays under great pressure due to farming and human occupation. Large areas of natural vegetation are being destroyed, causing concern about the future. Education is essential to increase ecological awareness.

Computer simulations are important tools for learning. They can complement and, in many cases, substitute field work. It is possible, for example, to control some environmental factors during simulations, and carry out experiments that cannot be done with real ecological systems. By doing so, learners can construct their own hypothesis and investigate them in the context of alternative scenarios. It is a generally held position that this 'learning by doing' will aid learning (cf. [deJong (editor), 1991]).

Qualitative simulations are particularly important for ecological domains, such as in the cerrado vegetation. Not only are quantitative data often almost non-existent, qualitative models also provide many additional features that are important for having learners interact with the simulation (see also [Bredeweg & Winkels, 1994; Bredeweg & Winkels, 1996]).

3 Qualitative Simulation Tool

We use GARP [Bredeweg, 1992] as our qualitative simulation tool. GARP takes as input a set of scenarios, a library of model fragments representing the domain knowledge, and a set of transition rules. When running GARP a specific scenario can be selected for simulation. The user can control the simulation in terms of deciding which transition to explore and for how long (one or more successor states). GARP can also be run to produce a full simulation (i.e. total-envisonment).

GARP uses the following building blocks for constructing a model. First, representation of simple (physical) entities and their structural relations. Second, representation of time varying properties in terms of quantities and quantity spaces. Quantity spaces are represented independently from a specific model. When building a qualitative model, quantity spaces are assigned to quantities and constraints can be specified between them. Third, representation of all kinds of dependencies between quantities and values of quantities.

Using these building blocks, initial scenarios can be specified as well libraries of model fragments. Scenarios usually consist of a structural description of the system and some initial values for certain quantities. Model fragments are rule-like, in terms of having conditions and consequences. The former specifies the structural descriptions and the specific quantity conditions that must hold in order for the model fragment to be applicable. The givens of a model fragment specify the behavioural features that can be derived. An important part of this is the specification of the causal model underlying the behaviour.

GARP uses a set of rules to reason about state transitions. In normal situations GARP takes a set of general (domain independent) rules for reasoning about terminations and their precedence. However, rules have a similar structure as model fragments and allow the knowledge engineer (or teacher) to represent a rich set of conditions if required. The latter can be important for focusing the simulation and it provides additional leverage for generating explanations.

4 Guidelines for Modelling

The construction of qualitative models is a difficult and often much time consuming task. One way to support the process of modelling is to learn from decisions made by previous modelling events. It is in this respect important to understand the activities involved in the modelling process as well as the critical decisions to be taken within these activities. In this section we present an initial set of guidelines for the modelling process. Our aim is to explicate the decisions we took during the construction of our models for ecology and to reformulate them as (more) general guidelines for constructing qualitative models.

4.1 Purpose of the Model

Modelling requires a great deal of idealisation. The purpose of the model gives the perspective the modeller should take when conceptualising the system to be modelled. The purpose of the model also gives the 'golden standard' for evaluation.

Two critical factors in understanding the purpose of a model are:

- the type of user, and

- the role of the model.

Starting with the former, it makes a big difference whether the constructed model is to be used by experienced ecologists or by students in secondary schools. It also matters what kind of task the user will perform with the model. A qualitative model can be used as a tool for inspecting the dynamics of some complex system (e.g. [Yip, 1995]). In this situation the emphasis will be on correct, complete and advanced simulations. In other situations however, different aspects may become more important. Particularly, in educational settings the realisation of 'articulated' models is important [Falkenhainer & Forbus, 1991].

For the models described in this paper the objective is to construct an Interactive Learning Environment (ILE) with which students can create their own models using a library of model fragments, run simulations and receive assignments and explanations [Salles *et al.*, 1997]. As a result the following aspects are important:

Interactive Simulation It is important that students can change the conditions of the simulation or the values of certain quantities, in order to have a better understanding of the system being simulated. The students should also be allowed to focus the simulation into directions they prefer. It is therefore important that the simulator is fully controllable by the student, so that it can be run step by step if required.

Model fragments as knowledge chunks Model fragments should represent 'stand-alone' parts of the domain knowledge that students should master. The idea is that each relevant domain concept (e.g. small population, germination, etc.) is expressed in one model fragment. Model fragments will therefore be an important ingredient for deriving an explanation.

4.2 Subsystem Selection

Selecting the subsystem to which a set of equations can be applied is standard practice in physics education (e.g. [Mettes & Roossink, 1981]. When building qualitative models we face a similar problem. We have to decide upon the system that will constitute the heart of the model. The subsystem selection will set the focus on what should be modelled and what will be left out.

For the model described in this paper we decided to represent the dynamics of the cerrado communities. Communities are complex entities consisting of many types of plants and animals. We have to abstract from the enormous diversity of organisms and define a finite set of representative entities. We applied the notion of 'functional group', commonly used by ecologists to describe communities in cerrado as groups of trees, shrubs and herbacous-graminoid plants. A functional group is a set of plants that have some common features and that display similar predictable behaviour when exposed to certain environmental factors. Each functional group can be seen as a population:

Population as a key concept Reasoning about changes in communities requires knowledge about populations [Salles *et al.*, 1996]. We have therefore developed a kernel of partial models that represents general knowledge about populations, which can be used in different situations.

4.3 Building an Ontology

Individuation

How to characterise the basic concepts that constitute the model? It is important to recognise permanent and temporary properties of the individuals with respect to the purpose of the model. When thinking about populations in ecology, decisions should be made whether to include features such as: sex, age classes, etc. In general, entities must be defined, as much as possible, on the basis of their permanent characteristics [Hayes, 1978].

Our choice was to represent populations as sets of individuals that can be affected by flows of 'born', 'dead', 'immigrated' and 'emigrated' individuals. This approach can be compared to the 'contained stuff' ontology used by [Collins & Forbus, 1989] to build models of thermodynamic processes.

Quantities and Quantity Spaces

Properties that change over time are typically represented by quantities and quantity spaces. Crucial for the accessibility and understandibility of a model by students is the amount of variation that is represented within these modelling primitives (too much variation will become confusing for a student). We refer to this as the:

Minimum required variation Build quantity spaces such that they facilitate the generation of all the qualitative distinct states that are important for the system at hand.

This rule can be operationalised in different ways. First, we can point out one or more critical quantities in a simulation and assign to these larger quantity spaces, and a more restricted one for the other quantities. Second, we can focus on deviations from a certain 'normal' value. In situations where the notion of equilibrium of the system is important, the quantity space {below-normal, normal, above-normal} can be used. Notice that 'relative' values can be linked to the other quantity spaces by different types of correspondences (see [Bredeweg, 1992]). Third, we can have simulations being based on inequality statements between quantities which can have only a single value. For example, two 'populations sizes' are both 'plus', but one is bigger/equal/smaller than the other. In all the cases described here, the resulting models capture a vocabulary that is focused on the relevant quantities and how these may vary. This makes a model easier to understand for students.

Processes and Actions

Following the idea of processes [Forbus, 1984] we represent changes as starting from direct influences which then propagate via indirect proportionalities. The notion of a causal model is crucial in an educational setting. However, additional vocabulary is required in order to capture many complex and intertwined processes in ecological systems. We explicitly use: subtype and consist-of hierarchy between processes. In addition we use the notion of agent models to account for human intervention [Bredeweg, 1992]. The subtype hierarchy is important in order to generate utterances such as: 'colonisation is a kind of immigration process that occurs when there's no population in a certain area'. Aggregated processes consists of the sum of a number of processes at a lower level. Sometimes the aggregated process has an ecological meaning and different vocabulary exists for reasoning about that (e.g. notion of population growth consisting of natality, mortality, immigration and emigration processes). Finally, in order to represent human actions that affect some ecological system we used the notion of an 'agent model'. Usually an agent model sets the value of a derivative, for example, the notion of 'conservation' is represented by decreasing fire frequency (see also Section 5).

4.4 Simplifying the Simulation

In an educational context, there is a limit to the number of states that can be dealt with by a student (both understanding and motivation become problematic when the set of states is too high). We employed two important mechanisms to simplify the simulation.

Model fragments as simplifying assumptions In order to reuse detailed model fragments in complex scenarios. it is often necessary to take a more abstract view of the system. In our model we realised more abstract views by defining model fragments that summarise certain variations at a lower level.

Focused state transitions State transitions have different probabilities of occurrence. Termination rules [Bredeweg. 1992] can also be used to reduce the number of possible states. by means of removing terminations with low probability. Using this approach the number of possible terminations the qualitative simulator considers at each state transition can be reduced considerably.

Both mechanisms implement a kind of simplifying assumption although the realisation in our model is rather different from [Falkenhainer & Forbus. 1991]. Instead of using the assumptions to select the required model fragments they explicitly limit the possible branching of the simulator. The set of used model fragments remains the same (for examples see Section 5.3).

5 Modelling Cerrado Vegetation

Following important research on the Brazilian cerrado vegetation ([Coutinho, 1990; Pivello, 1992; Moreira, 1992]) our models should support explanations about the relation between fire frequency and the structure of the vegetation, expressed as follows:

- If the fire frequency decreases, for example because of human actions, then succession will occur and as a consequence the vegetation will evolve and become denser, with more trees and shrubs and less grass.
- If the fire frequency increases, then a degradation process is active and the vegetation tends to become more open, with less trees and shrubs and more grass.

Given a certain scenario or initial problem, the models should allow the students to make predictions and postdictions about the system (cf. [Forbus, 1984]). Typically, the models should facilitate derivations such as "the campo sujo changed to campo cerrado because fire frequency decreased". They should also provide access to the underlying causal models that represent how these changes follow from different responses of populations of trees, shrubs and grass to environmental influences such as light, humidity and temperature. As mentioned before, reasoning about changes in communities requires knowledge about populations.

5.1 Models of Populations

Populations consist of groups of individuals of the same kind, living in a certain place, during a certain period of time. The size of the population is an important factor, because it is an indication of the balance of the forces acting on the individuals. The quantity introduced to express this is: Number-of. It can take on values from different quantity spaces, depending on the objectives of the model. We used mainly the quantity space {zero, low, medium, high, maximum} to describe the 'absolute' qualitative values, and make comparisons between populations.

Following our assumption that each relevant concept should be represented by a model fragment, we defined fragments for the concepts: small, medium, large, maximum sized, non-existent and extinct populations. Behaviour is expressed in model fragments representing the notions of increasing, decreasing and steady populations. We included also definitions of populations of trees, shrubs and grass, the most used types of organisms represented in these models (see also Figure 2).

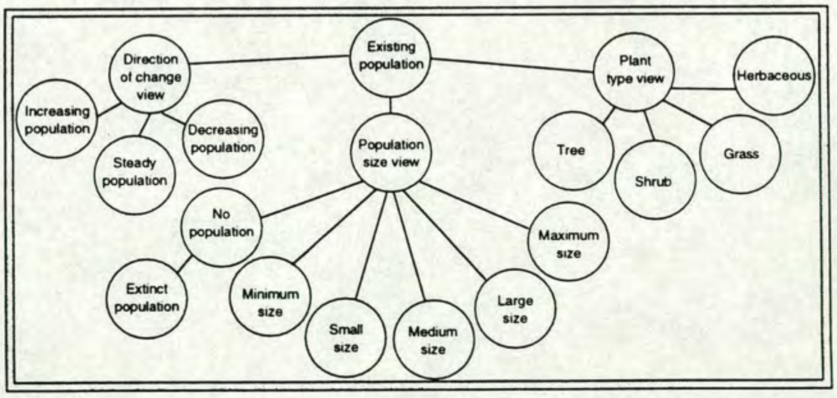

Figure 2: Model fragments hierarchy of populations

In order to predict changes in populations and to build explanations about the results of simulations, we need a vocabulary to express the basic processes affecting the individuals. They are being born (natality), they die (mortality), they arrive from elsewhere (immigration), and they may leave (emigration). Changes in the size of a population depend on the balance of these processes. The four basic processes introduce the following quantities (rates): Born-flow, Dead-flow, Immigrated-flow and Emigrated-flow. These flows have the quantity space {zero, plus}, because they cannot be negative. Subtypes of the basic processes were defined to take into account some particularities. For example, instances of natality and mortality processes were used to describe how environmental factors can influence the Born-flow and Dead-flow in trees, shrubs and grass. Also we defined the colonisation process as a subtype of immigration.

Note that these processes are independent of each other and as such do not (individually) define the final direction of change in the size of the population. We need the additional notion of population growth to express how the basic processes combine in a particular situation. The population growth process is defined as an

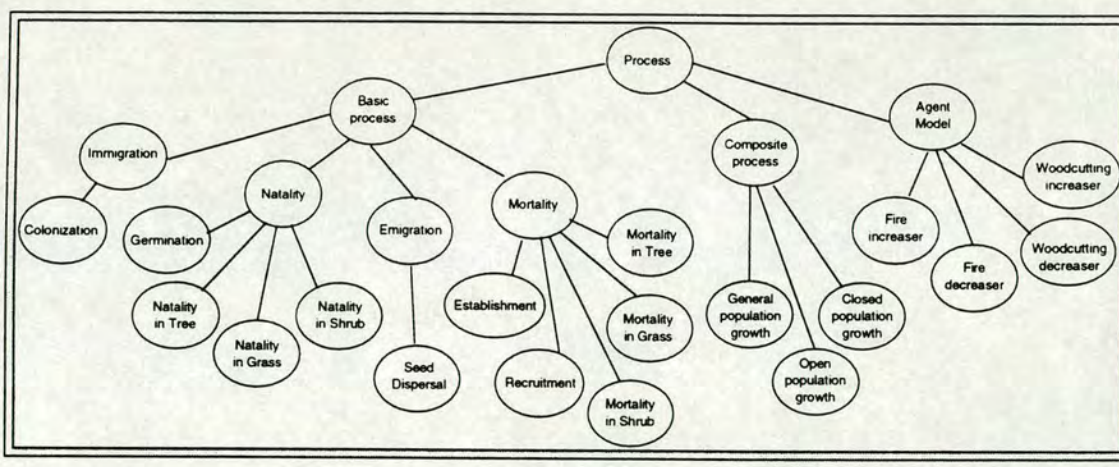

Figure 3: Model fragments hierarchy of Processes

aggregation of the four basic processes and represents a unique flow. It introduces the quantity Growth-rate with the quantity space {minus, zero, plus}. Growth-rate can be calculated by the addition of the amount of individuals represented in each flow. The hierarchy of processes is shown in Figure 3.

5.2 Models of Communities

Communities are groups of populations. Communities in cerrado can be classified according to the Number-of trees, shrubs and grass. Typically, researchers (cf.

[Coutinho. 1990]) classify the cerrado into: campo limpo. campo sujo. campo cerrado. cerrado sensu stricto and cerradao. In order to model this classification we created model fragments representing each of them. Some intermediate communities were included. to help the understanding of the transitions (see also Figure 4). The

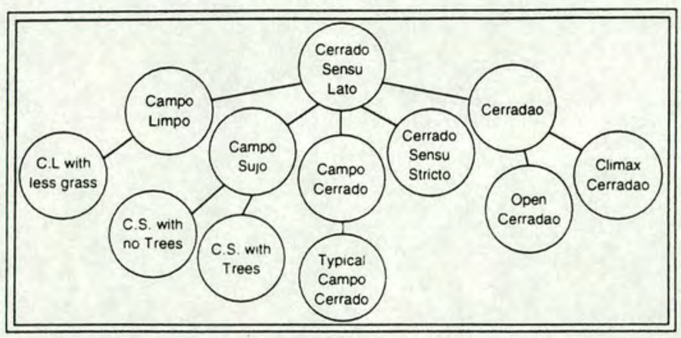

Figure 4: Model fragments hierarchy of communities

values used to characterise the main types of communities are presented in Table 1.

	Grass	**Shrub**	**Tree**
campo limpo	$> med$	$= zero$	$= zero$
campo sujo	$= high$	$= low$	$< med$
campo cerrado	$> zero$ & $< max$	$> zero$ & $< max$	$= med$
cerrado sensu stricto	$= low$	$>= med$	$= high$
cerradao	$= zero$	$= high$	$> med$

Table 1: Classification of typical cerrado communities

The cerrado communities are related to a general ecosystem, the cerrado sensu lato. The model fragment that defines the cerrado sensu lato specifies relevant properties of the micro-environment at the surface of the soil. It introduces the quantities Nutrient, Humidity, Light and Temperature. These quantities are related to the amount of Litter, the dead material that covers the ground (leaves, small pieces of wood and other parts of plants). We assume that these factors are always present in any scenario described by the models. Thus, their quantity space is {plus}.

The canopy of the trees has an important influence on the factors mentioned above. In our models this is represented by the quantity Cover, with the same quantity space as used for the population of trees. It is assumed that there exists a direct correspondence between the Number-of trees and the amount of Cover: the value taken by the former is also assigned to the latter. For example, if the value of Number-of trees is low, then Cover is also low.

All the above mentioned factors are influenced by fire. Fire frequency is a component of the so called 'fire regime' [Whelan, 1995]. It expresses how often a vegetation is burned. In the model this is represented by the quantity Fire-frequency, which can take on values from the quantity space {zero, plus}. Fire frequency changes as a consequence of human actions. This is modelled by using agent models.

The influence from fire frequency on the community is indirect: it propagates through the described network of environmental factors that finally influences the basic processes of plant populations. Altogether, 16 direct influences (I) and 32 indirect influences (P) affecting 33 quantities constitute the full structure of the causal model, as shown in Figure 5.

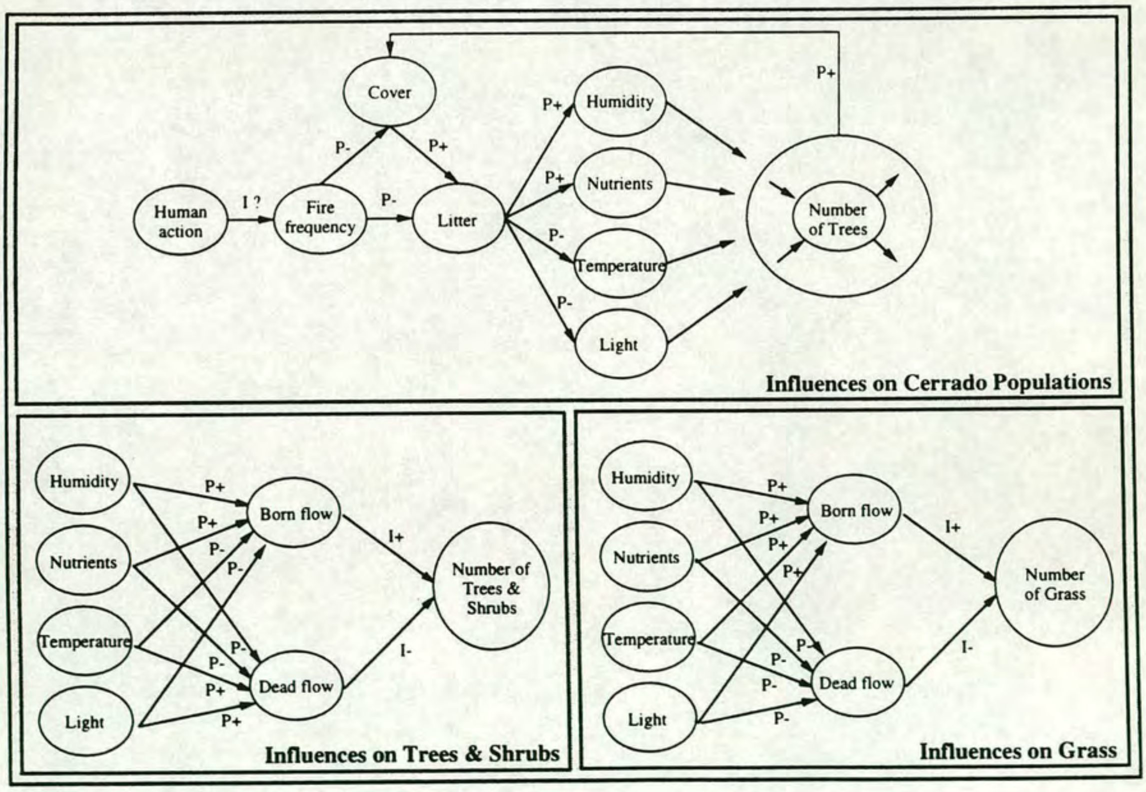

Figure 5: Causal model for the cerrado communities

5.3 Results from Simulations

We ran several simulations with the model. One of the simulations produced the envisonment graph depicted in Figure 6. It shows the successional changes in cerrado predicted by the hypothesis presented in the beginning of this section. In order

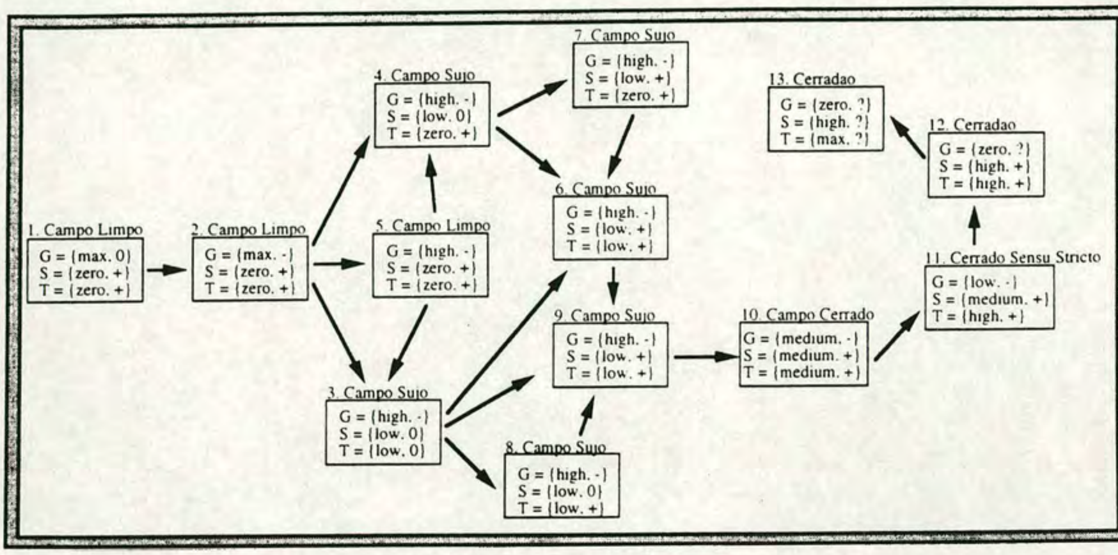

Figure 6: Succession in cerrado vegetation

to reduce the number of ambiguities and possible states in the full simulation, we added a few assumptions to the model. The most important one was redefining the campo cerrado as a typical community with the values for trees, shrubs and grass being equal to 'medium'. The effect can be seen in the graph: there is some branching for the campo limpo and campo sujo communities, but the envisonment then moves in a straight line from campo cerrado up to cerradao. We also removed the influences from Humidity and Nutrient on the population of grass in order to reduce ambiguity. For all simulations we employed the 'Minimum required variation' rule when assigning quantity spaces to quantities. Finally, we adapted some termination rules in order to remove many 'impossible' transitions that the simulator was trying. For example, as long as there exists a population, the natality process will be active. However, due to environmental factors the Born-flow may decrease, triggering a termination to zero. An assumption specifies that this termination can only happen when the population becomes extinct. Adding assumptions such as these speed up the simulation process, and more important, make the result transparent and therefore easier to understand.

The resulting qualitative models offer several possibilities for tutoring. Using different initial scenarios, it is possible to explore selected parts of the causal path. For example, we can analyse the effect of each factor on the populations, or the effects of a group of factors on a specific population, etc.

6 Discussion and Concluding Remarks

The construction of reusable domain models is an important goal both to researchers in qualitative reasoning and ecology. In this paper we have presented a library of model fragments for reasoning about the behaviour of ecological communities. We have developed a kernel of partial models that represents general knowledge about populations, which can be (re-)used in different situations. The models are implemented in GARP [Bredeweg, 1992], a qualitative simulation environment implemented in Prolog.

The construction of qualitative models is a difficult and often much time consuming task. Supporting the modelling process requires an understanding of the activities involved as well the critical decisions to be taken within these activities. In this paper we have discussed a set of initial guidelines for the construction of qualitative models, based on our experience in representing the ecology of fire in the Brazilian cerrado vegetation.

The purpose of a model is an important overall factor in determining how to conceptualise and represent a certain system. Our domain of application is ecology and the models are used as the basis for educational tools for teaching ecological awareness. In this paper we discuss how notions such as, (1) fully interactive simulation, (2) model fragments as knowledge chunks, (3) population as a key concept, and (4) basic processes, aggregated processes, and 'agent models' are important for the construction of qualitative models that can be used in an 'guided discovery' oriented educational setting. Being concerned with teaching also requires that simulation models have a limited size, otherwise they become intractable for students. We have discussed how simplifying assumptions can be employed for this. Our approach differs from [Falkenhainer & Forbus, 1991] in that we limit the possible variations of the simulator, while the set of used model fragments remains the same.

We are currently improving the prototype of the ILE and its capacity of generating explanations [Salles *et al.*, 1997]. The work includes:

- expanding the library, in order to reason about fuel dynamics, climatic changes and other aspects of fire on the cerrado vegetation;
- describing the life cycle of cerrado plants, that is describing flowering, fruit production, seed production, germination, and the survival of young plants. Each of these stages can be affected by fire and there are several interesting points to be explored (particularly from the educational point of view);
- creating different simulations to produce explanations in specific contexts. We are creating tasks and problem solving situations for the students to explore the learning environment.

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Deriving Explanations from Qualitative Models

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Abstract

Qualitative computer simulations have great potential for teaching people to understand and interact with their physical environment. Prerequisite for using that potential, is that these simulations can be explained to humans in ways that they comprehend. Preferably, these explanations should be generated on the basis of the qualitative models that underly the simulations, to avoid having to handcraft the explanations for every new domain. The research that we describe in this paper deals with exactly that problem. It combines two lines of earlier research: representing qualitative models, GARP [2], and didactic discourse planning, DDP [13]. All qualitative models represented in GARP can be questioned by students, using an as yet limited set of questions, that will be answered by a generic didactic discourse planner. The overall interaction between students and systems is guided by a 'mental tour' through the successive states of the simulation (the 'envisionment graph'). At each state several questions can be asked. These questions are linked to 'information needs', the topics of discourse. On the basis of these topics, the discourse planner will plan sequences of utterances, taking into account such things as the students beliefs, and the state of the discourse process.

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1 Introduction

Early systems such as SOPHIE [4] and STEAMER [6] can be seen pioneering landmarks in trying to have computers communicate knowledge about the behaviour of (physical) systems with students. Efforts such as these gave raise to an area of AI research known as Qualitative Reasoning (QR). In this paper we investigate how qualitative models can be used for explanation purposes. Our work combines two lines of earlier research: representing qualitative models, GARP [2], and didactic discourse planning, DDP [13]. We have constructing a prototype of an Interactive Learning Environment (ILE), based on the qualitative models implemented in GARP, that can be consulted by students to investigate the behavioural characteristics of some (physical) system. The specific domain that we are dealing with in this paper is the ecology of the Brazilian cerrado vegetation and the effects of fire on this vegetation. It provides a diversified set of problems for exploring the possibilities of automatic generation of explanations.

2 Ecology in Brazilian Cerrado

The central region of Brazil is covered by a vegetation called cerrado. This huge area of almost 2 million square kilometres is characterised by a tropical climate, with two well marked seasons (wet and dry), and by soils that have low fertility. Within the cerrado vegetation it is possible to identify several types of cerrado physiognomies, spanning from open grasslands to more or less closed forests. These physiognomies have well defined floristic composition and are mainly determined by fire, soil fertility and the amount of water available in the soil during the dry season. Researchers have investigated the effects of fire on the cerrado (e.g. [5, 8]). It has been shown that fire can affect both physical and biological factors: fire causes changes on (1) the energy flux, (2) water and nutrient cycles, (3) the species composition of communities, (4) the biomass in many plants, and (5) stimulates flowering and germination of seeds in many species. Fire can therefore be used as a management tool, for example to stabilise the vegetation in certain areas, and to reduce the risk of big fire events [9]. Qualitative simulations are particularly important for ecological domains. Not only are quantitative data often almost non-existent, qualitative models also provide many additional features that are important for having learners interact with the simulation (see also [3]).

3 Modelling the Cerrado Vegetation

Following important research on the Brazilian cerrado vegetation [5, 9] our models should support explanations about the relation between fire frequency and the structure of the vegetation, expressed as follows: (1) If the fire frequency decreases, for example because of human actions, then succession will occur and as a consequence the vegetation will evolve and become denser, with more trees and shrubs and less grass. (2) If the fire frequency increases, then a degradation process is active and the vegetation tends to become more open, with less trees and shrubs and more grass. The models should provide access to the underlying causal models that represents how these changes follow from different responses of populations of trees, shrubs and grass to environmental influences such as light, humidity and temperature. Next to these more general modelling requirements we enforced a number of additional requirements in order to make the model useful for our teaching purposes (see also [10] for details):

Population as a key concept Reasoning about changes in communities requires knowledge about populations [11]. We have therefore developed a kernel of partial models that represents general knowledge about populations which can be used in different situations.

Model fragments as knowledge chunks Model fragments should represent stand-alone parts of the domain knowledge that students should master. The idea is that each relevant domain concept should be expressed in one model fragment. Model fragments will therefore be an important ingredient for deriving an explanation.

Assumptions as simplifying model fragments In order to reuse detailed model fragments in complex scenarios (problem situations) it is often necessary to reduce the range of the model. In other words, more complex scenarios usually require a more abstract view in order to keep the interpretation of the simulation tractable. In our model we realised more abstract views by defining model fragments that summarize certain variations at a lower level.

Aggregated processes and agent models Typically in ecology, different vocabulary exists for reasoning about changes in an ecological system at different levels of detail. In order to be able to represent this aspect we introduced the notion of an 'aggregated process'. It consists of the sum of a number processes at a lower level. In order to represent actions performed by humans within an ecological system we use the notion of an agent model [2]. Usually an agent model sets the value of some derivative, such as a decrease in fire frequency representing the notion of 'conservation'.

3.1 Models of Populations

Populations consist of groups of individuals of the same kind, living in a certain place, during a certain period of time. The size of the population is an important factor (Number-of), because it is an indication of the balance of the forces acting on the individuals. It can take on values from different quantity spaces, depending on the objectives of the model. For example, we used the quantity space {zero, low, medium, high, maximum} to describe the 'absolute' qualitative values, and make comparisons between populations.

Following our assumption that each relevant concept should be represented by a model fragment, we defined fragments for the concepts: small, medium, large, maximum sized, non-existent and extinct populations. Behaviour is expressed in model fragments representing the notions of increasing, decreasing and steady populations. Combining them we can say, for instance, "the population is small and increasing".

In order to predict changes in populations and to build explanations about the results of simulations, we need a vocabulary to express the basic processes affecting the individuals: natality, mortality, immigration, and emigration. These basic processes introduce the following quantities (rates): Born-flow, Dead-flow, Immigrated-flow and Emigrated-flow. These flows have the quantity space {zero, plus} (they cannot be negative). Note that these processes are independent of each other. We need the notion of population growth to express how the basic processes combine in a particular situation. The growth process is defined as an aggregation of the four basic processes and represents a unique flow (the addition of the individual flows). It introduces the quantity Growth-rate with the quantity space {minus, zero, plus}.

3.2 Models of Communities and Ecosystems

Communities are groups of populations. Communities in cerrado can be classified according to the Number-of trees, shrubs and grass. Typically, researchers classify the cerrado into: campo limpo, campo sujo, campo cerrado, cerrado sensu stricto and cerradao [5]. The cerrado communities are related to a general ecosystem, the cerrado sensu lato. The model fragment that defines the cerrado sensu lato specifies relevant properties of the micro-environment at the surface of the soil. It introduces the quantities Nutrient, Humidity, Light and Temperature. These quantities are related to the amount of Litter, the dead material that covers the ground (leaves, small pieces of wood and other parts of plants). We assume that these factors are always present in any scenario described by the models. Thus, their quantity space is: {plus}.

The canopy of the trees has an important influence on the factors mentioned above. In our models this is represented by the quantity Cover, with the same quantity space as used for the population of trees. It is assumed that there exists a direct correspondence between the Number-of trees and the amount of Cover: the value taken by the former is also assigned to the latter. For example, if the value of Number-of trees is low, then Cover is also low.

All the above mentioned factors are influenced by fire. Fire frequency is a component of the so called 'fire regime' [12]. It expresses how often a vegetation is burned. In the model this is represented by the quantity Fire-frequency, which can take on values from the quantity space {zero, plus}. Fire frequency changes as a consequence of human actions. This is modelled by agent models.

The influence from fire frequency on the community is indirect: it propagates through the described network of environmental factors that finally influences the basic processes underlying populations. Altogether, 13 direct influences (I) and 28 indirect influences (P) constitute the structure of the causal model, as shown in Figure 1.

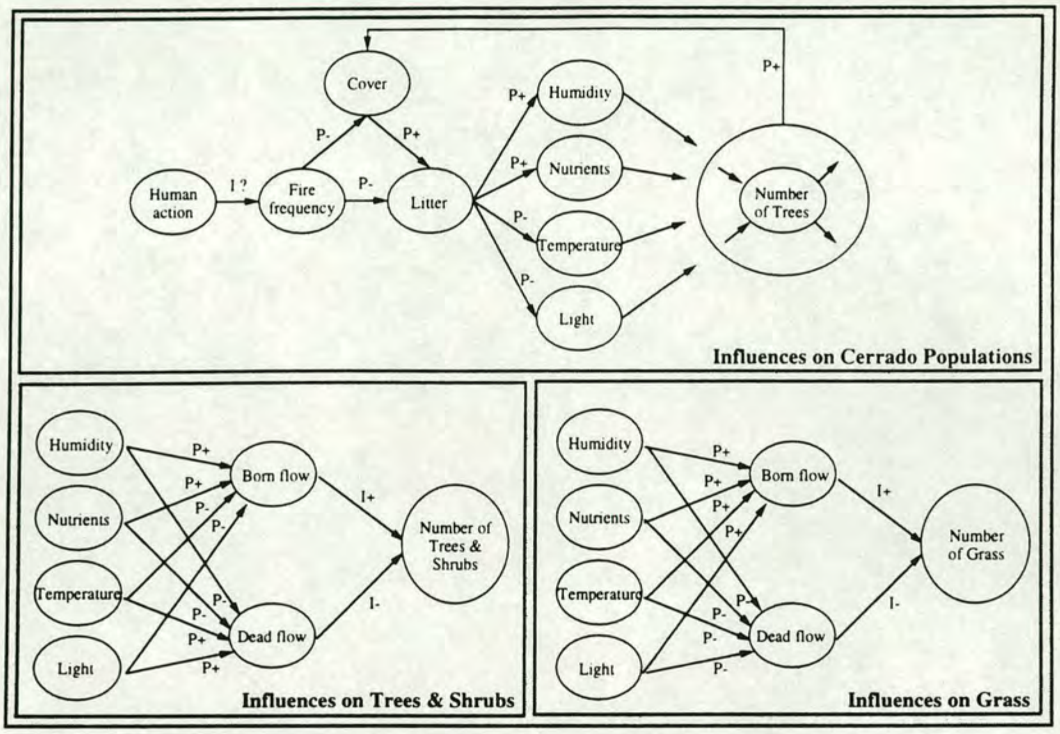

Figure 1: Causal model for the cerrado communities

3.3 Results from Simulations

A simulation with this model produced the envisonment graph depicted in Figure 2. It shows the successional changes in the cerrado predicted by the hypothesis presented in the beginning of this section. In order to reduce the number of ambiguities and possible states in the full simulation, we made some assumptions. The most important one was redefining the campo cerrado as a typical community with the values for trees, shrubs and grass equal to medium. We also removed the influences from Humidity and Nutrient on the population of grass in order to reduce ambiguity.

The resulting qualitative models offer several possibilities for tutoring. Using different initial scenarios, it is possible to explore selected parts of the causal path. For example, we can analyze the effect of each factor on the populations, or the effects of a group of factors on a specific population. Currently we are expanding the library, to be able to represent other aspects of the ecology of fire in the cerrado.

4 Generating explanations

In the literature there are at least two fundamentally different approaches to generating explanations. One is based on typical rhetorical structures of explanations, represented in so called *schemata*, and is exemplified by McKeown's TEXT system [7] for answering questions about a database. The second major approach to explanation is that of using planning formalisms to dynamically plan sequences of utterances to achieve certain communicative goals. It is exemplified by Appelt's work on KAMP [1].

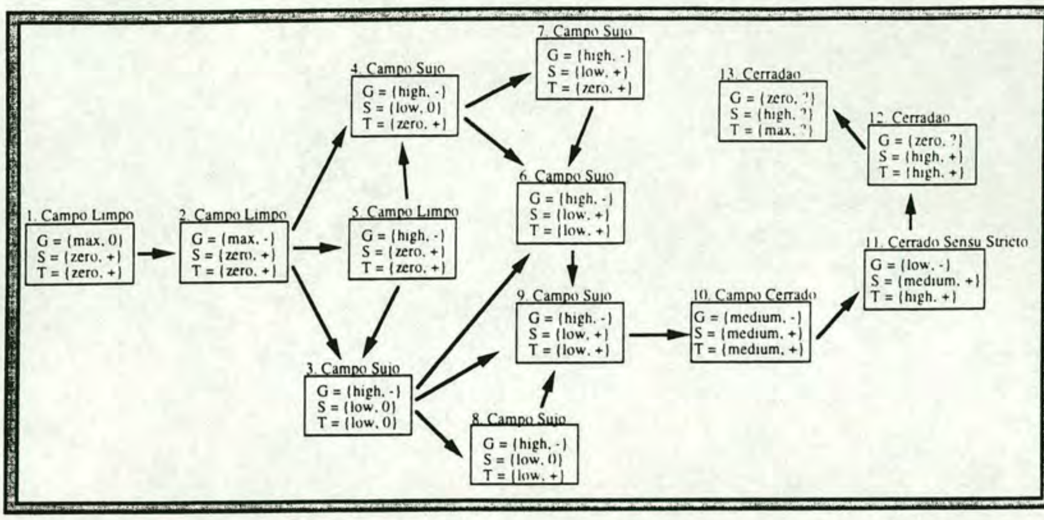

Figure 2: Succession in cerrado vegetation

In the EUROHELP project, Winkels used a combination of the schemata and planning techniques in his didactic discourse planner [13]. Discourse strategies are planned on the basis of communicative goals, but the starting point is a library of 'skeletal plans' that have worked in the past. Only when these strategies do not work, general fall-back strategies are refined to meet the current information need. The skeletal strategies can be viewed as hierarchical schemata, that still contain the communicative (sub)goals they are supposed to meet. It is this last approach we will follow in this research.

The overall interaction between students and the ILE is guided by a 'mental tour' trough the successive states of the simulation (the 'envisionment graph'). At each state several questions can be asked. These questions are linked to 'information needs', the topics of discourse. On the basis of these topics, the discourse planner will plan sequences of utterances, taking into account such things as the students beliefs, and the state of the discourse process.

4.1 Asking questions

At present, the student can ask the following questions about a simulation in a specific state:

1. What are the system elements in the present state? This is asking about basic concepts, its instances, its attributes and values, and relations between concepts or instances.

2. What are the initial causes of change in the state? This is asking about processes and agents that can cause change. Causality is modelled as 'influences' between quantities. Agents will be given in the input system. Inequalities between quantities may trigger a process (e.g. quantity 'Number-of' greater than zero will trigger a mortality process).

3. How does change propagate to other quantities in the present state? This is asking about 'proportionalities' between quantities, and possibly new 'influences'.

4. How does a particular quantity change over states? This is asking about values and derivatives of a quantity. For a specific quantity, it is easy to find its value and derivative in every state of the simulation.

Questions are formed by filling a text form or template with instances from the simulation. There is a logical order in these questions. One cannot ask (or explain) propagation of change, before one knows about the initial causes of change, etc. Therefore, questions have preconditions attached to it, that check whether the necessary prerequisite information is already available. Given a student's question, we have to determine *what* to say, i.e. what his or her information need is, what the topic(s) of the interaction will be. This is what McKeown calls the 'relevant knowledge pool' [7], or Winkels calls the 'topicalization' process [13]. Since there is no task the student is supposed to do (except for understanding the 'cerrado' model), there is no generic diagnostic process that tries to infer the student's information need when he or she asks a question. A procedure to determine the initial topic is directly linked to the questions. These initial topics can be shortened or extended by the discourse planner when needed (see below). An example question is:

Type: Propagation of influence X within state
Conditions: Influence X has been introduced
Template: "How does X propagate in this state?"
Procedure: Find all proportionalities between the quantity that is being influenced X and other quantities. Look recursively for influences or proportionalities with these other quantities until no more can be found.

We will illustrate the workings of such a 'topicalization' procedure for the simulation shown in Figure 1. The scenario specifies a population of grass ('population3'), and a human agent called 'fire-decreaser1'. The initial change is caused by the human agent 'fire-decreaser1' which causes a decrease in 'fire-frequency1'. Now the question: "How does the negative influence of fire-decreaser1 on fire-frequency1 propagate in this state?", leads to a topic in the following way. First, find all proportionalities between 'fire-frequency1' and other quantities. There is only one in this state, a negative proportionality with 'litter1' (fire will burn litter on the ground). Now look for influences or proportionalities on this other quantity: positive proportionalities with 'moisture1' and 'nutrient1' (litter provides nutrients and will keep the soil moist), negative proportionalities with 'light1' and 'temperature1' (litter will block light and warmth). And again, for all these quantities, look for influences or proportionalities on them, etc.

```
[ inf-neg-by(fire-frequency1,fire-decreaser1),
  [ prop-neg(litter1,fire-frequency1),
    [ prop-pos(moisture1,litter1), [],
      prop-neg(light1,litter1),
        [ prop-pos(born-flow3,light1), [inf-pos-by(number-of-3,born-flow3), []],
          prop-neg(dead-flow3,light1), [inf-neg-by(number-of-3,dead-flow3), []]
        ],
      prop-pos(nutrient1,litter1), [],
      prop-neg(temperature1,litter1),
        [ prop-pos(born-flow3,temperature1),
            [inf-pos-by(number-of-3,born-flow3), []],
          prop-neg(dead-flow3,temperature1),
            [inf-neg-by(number-of-3,dead-flow3), []]
]]]]
```

4.2 Planning the explanation

Next, plan the interaction that is aimed at getting the needed information across to the user. This planning process is done by a generic *Didactic Discourse Planner* (DDP) [13]. Basically, DDP takes the information need ('local need') and first looks in a library of skeletal discourse strategies to see if one of those is applicable in the current situation. If it is, it is instantiated to the current situation, and the strategy will be transformed to natural language and presented to the student. If none can be found, general fall-back strategies will be refined to deal with the situation. The strategies take care of skipping or summarizing information, possibly extending parts, sequencing it, minimizing shifts of focus, etc.

DDP's strategies implement general principles for (didactic) discourse, of which the two most important ones are:

Given $\longrightarrow$ New. Always try to link new information to given, or "known" information. Practically, this means linking new information to: Something the student already knows (Student Model), something that has recently been taught (Coaching History), something that had just been mentioned (Discourse Model), or something that has just happened (Performance History).

Conciseness and relevance. Try to be to the point, do not explain things the student already knows, or is assumed to know. Do not introduce new topics, unless necessary for understanding the new information. Whenever possible, use references to existing ('given') information instead of describing a topic again (cf. 'given-new' principle above). An interesting example is explaining a topic when a *similar* topic is known, or has just been described. In that case, focus on the differences.

4.3 Explaining Qualitative Primitives

As mentioned before, the overall interaction between a student and the ILE is guided by a tour through the *envisionment graph* (see Figure 2). The student can ask questions that lead to topics (information needs) to be handled by the discourse planner. The discourse strategies take care of general rational, and didactic principles at the higher levels, but the utterances at the lowest, 'executable' level will have to map onto the knowledge representation of the qualitative simulator, i.c. GARP. In this section we will discuss the ways to explain the GARP primitives, and show how these primitives can be combined to assemble more complex explanations.

For the primitives we represent:

Type: Label to indicate its use;
KR: the GARP knowledge representation it maps onto;
Loc: Where the instantiations for the current simulation can be found in the state description;
Known: The information that should be known or given in order for the primitive to be used (a special type of condition). This means, the information should be either in the student model or the discourse model of the current session;
Cond: Other conditions that need to be met for this version of the primitive to be used. They may refer to the current state of the simulation (e.g. the value of a derivative), and the current state of the discourse (e.g. topic in focus);
NL: The natural language expression for the primitive when the conditions are met.

We distinguish the following primitives:

1. Explaining basic concepts: These building blocks are used to explain system elements of a simulation, their attributes, and their interrelations (the 'isa' hierarchy).
2. Explaining quantities of an instance, their values, value ranges, and derivatives.
3. Explaining a causal dependency between quantities: Used for explaining direct causality (modelled as influences) and indirect causality (modelled as proportionalities).
4. Explaining constraints between quantities and/or values.

An example primitive is:

```
Type:    explaining a quantity, its value, and derivative (no value scope)
KR:      Generic Name( Instance, Inst Qname, continuous, Qspace )
         value( Inst Qname, unk, Value, Derivative )
Known:   Instance
Where:   in list of parameters and par_values in a predicted state (SMD)
Cond:    Derivative is plus; Qspace is only Value; focus on Inst Qname
NL:      "Inst Qname is the quantity Generic Name of Instance.
          It has currently the value Value and is increasing.''
```

4.4 Combining primitives

In answering questions, the discourse planner will eventually combine the primitives. For the example question presented above, concerning the propagation of change of the decreasing fire frequency, this may result in an explanation as the following:

```
[context]
  [remind basic concept]
    You know: There is a cerrado referred to as cerrado1
  [remind quantity]
```

```
    You know: cerrado1 has a quantity fire frequency referred to as
      fire-frequency1. It has currently the value plus and is decreasing.
[new information]
  [explain causal dependency]
    The decrease in fire-frequency1 increases the litter1
    [explain quantity]
      litter1 is the quantity litter of cerrado1.
      It has currently the value plus and is increasing.
  [signalling]
    The increase in litter1 has four effects:
  [explain causal dependency]
    1. The increase in litter1 increases the moisture1
  [explain causal dependency]
    2. The increase in litter1 increases the nutrient1
  [explain causal dependency]
    3. The increase in litter1 decreases the light1
       [explain causal dependency]
         The decrease in light1 decreases the born-flow3
         [explain quantity]
           born-flow3 is the quantity born-flow of grass1.
           It has currently the value plus and is decreasing.
         [explain causal dependency]
           The decreasing amount of born-flow3 decreases the number-of3
           [explain quantity]
             number-of3 is the quantity number-of of grass1.
             It has currently the value max and is stable.
       [explain causal dependency]
         The decrease in light1 increases the dead-flow3
         [explain causal dependency]
           The increasing amount of dead-flow3 decreases the number-of3
  [explain causal dependency]
    [explain similar]
    4. The increase in litter1 decreases the temperature1
       [refer same]
         This propagates the same way as light1
       [explain difference]
         but now for temperature1
```

5 Discussion and Concluding Remarks

In this paper we have described the initial results of a research project designed to create an ILE combining previous work in representing qualitative models, GARP [2], and in didactic discourse planning, DDP [13]. Our objective was to explore how the primitives used for building the qualitative models can be used to support explanations.

We built a set of qualitative models that represent some widely accepted hypothesis about the effects of fire on the vegetation dynamics of the Brazilian cerrado. In modelling this domain requirements were formulated in order to make the resulting model more useful for teaching purposes. Particulary, the notion of having model fragments represent stand-alone parts of the domain knowledge that students should master was important in this respect.

The qualitative models and the results of the simulations were used by the DDP to create the explanatory discourse. Although the current state of the prototype does not allow for the full use of DDP's explanatory possibilities, the students can inspect the qualitative models and the reasoning process, and ask questions about them. Given a particular question, a set of procedures is triggered to decide what to say. The topics selected are worked out according to a set of general tactical and strategical principles by the discourse planner. Next, using GARP's primitives, the system collects the knowledge to compose the answer. The primitives are finally combined and an answer for the question is produced. Some examples of how the main elements in the discourse map into the knowledge represented in the qualitative models are presented in this paper.

We are currently extending the ILE prototype in order to cover a broader range of facilities already present both in GARP and in DDP. This includes a more detailed ontology to represent the ecology of the cerrado, the definition of tasks and problems to be solved by the students in order to provide more context for the generation of explanations, and a refinement in the process of mapping the primitives of qualitative models and the domain concepts.

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